Reconciling Potential and Practice

Towards the Implementation of Nature-based Solutions for Climate Change Mitigation

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Abstract

Recent years have seen increased attention to the role that *nature-based solutions* (NbS) – activities that work in and with nature to address global societal challenges – can play in mitigating and adapting to climate change, protecting biodiversity, and improving human well-being. *Natural climate solutions* (NCS) – a subset of NbS that focuses on the protection and enhancement of natural ecosystems to improve carbon sequestration – can contribute up to a third of the cost-effective carbon dioxide mitigation needed to hold global warming below 2 degrees Celsius. To have the biggest effect on reducing global temperatures, however, NbS must be scaled up now and designed for the long-term. Yet, uptake of NbS continues to be slow and there remains a clear gap between the lagging action at scale and the promising research and policy narratives. This demonstrates an urgent need to better understand the implementation conditions for NbS. Currently, the evidence base on NbS remains incomplete, especially when it comes to systematically assessing effectiveness and implementation requirements. In particular, important contextual information on culture, behavior, and other social and institutional factors are lacking in large-scale assessments. The multiple benefits of NbS also remain undervalued, or in some cases are not valued at all. As such, the objective of this thesis is to conduct policy-relevant research that can contribute to closing the gap between the high potential for nature-based solutions to address global challenges, particularly climate change mitigation, and the realities of slow implementation in practice. Drawing on the existing literature on NbS, I argue that three building blocks are essential to driving successful implementation of any NbS activity, in particular at scale: (1) knowledge synthesis; (2) planning & decision-making; (3) policy & financing mechanisms (**Figure A**). I explore these in this thesis, contributing evidence and reflection on theoretical and methodological gaps in their assessment, as well as new perspectives. I achieve this in three ways. First, I systematically review the literature on enabling factors for NCS. Here, I highlight the role of synthesis in understanding how normative assumptions and narratives are shaped and in identifying gaps that risk leading to imbalances and lack of representation in decision-making processes. Second, I extend my findings from the review that indicate the importance of social factors and investigate entry points for integrating social aspects with computational models (IAMs) for NbS. In doing so, I provide new perspectives to discourse on why social sciences are underrepresented in IAMs and how this can be addressed, including via stakeholder engagement. Last, I zoom in on one type of NbS – forests activities – and present a novel theoretical framework for capturing the current and future value of forest co-benefits. This framework builds on the existing theoretical literature and provides a foundation for application in natural ecosystems beyond forests. My results emphasize that, given

the complex and multifaceted characteristics of the challenges on the ground, driving implementation at scale requires thinking about NbS with holistic and interdisciplinary perspectives. Future research avenues should refine and expand the use of systematic methods to comprehensively assess best practices and lessons for implementation and delve deeper into the implications of NbS for a just transition to a green economy, including trade-offs and side effects.

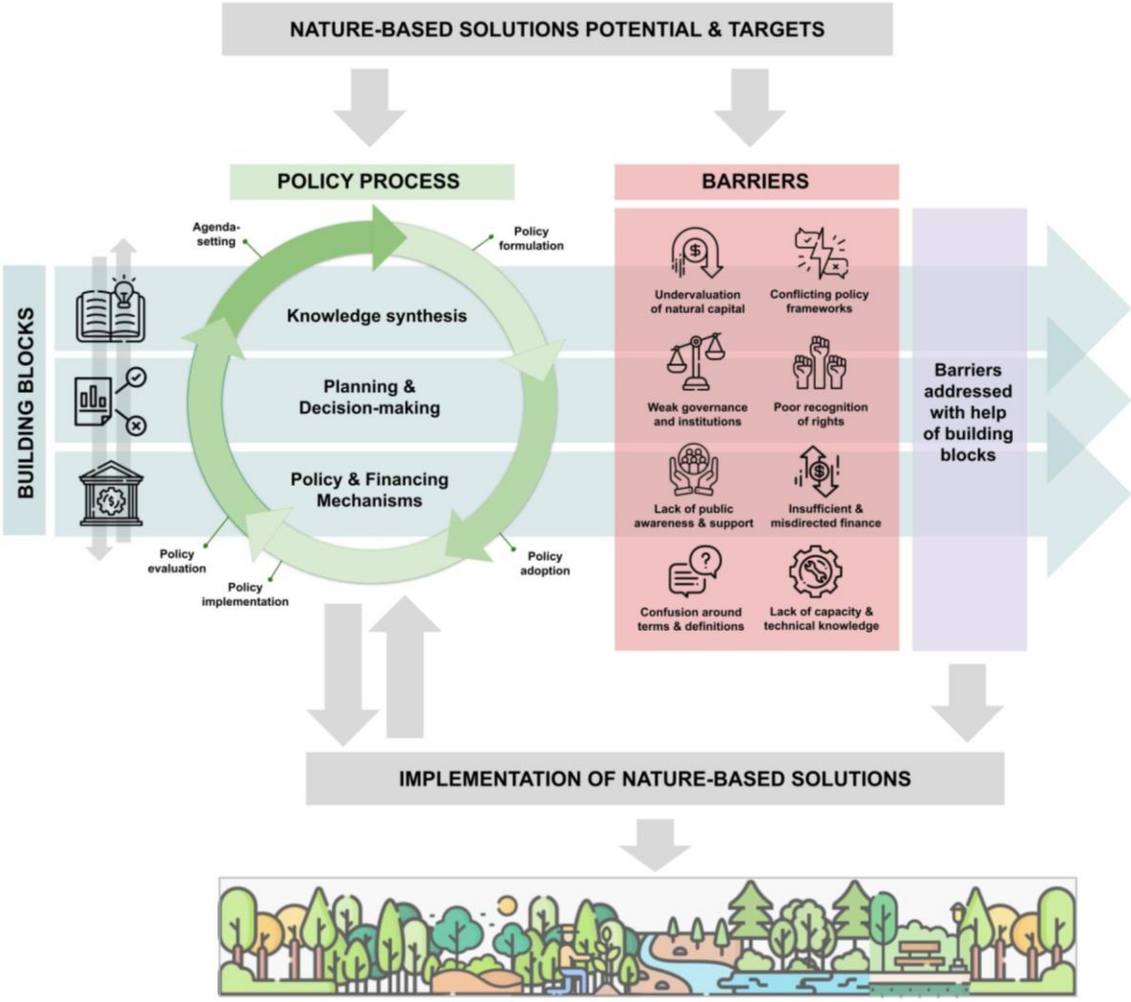

Figure A. Conceptual diagram of NbS potential to implementation (own illustration; see **Appendix** for icon image credits).

Zusammenfassung

In den letzten Jahren hat die Rolle naturbasierter Lösungen (*Nature-based Solutions*, NbS) – Aktivitäten, die in und mit der Natur arbeiten, um globale gesellschaftliche Herausforderungen zu bewältigen – bei der Abschwächung und Anpassung an den Klimawandel, dem Schutz der Artenvielfalt und der Verbesserung des menschlichen Wohlbefindens an Bedeutung gewonnen. Natürliche Klimalösungen (*Natural Climate Solutions*, NCS) – eine Untergruppe von NbS, die sich natürliche Ökosysteme mit dem Ziel der Kohlenstoffbindung schützt und verbessert – können bis zu einem Drittel der kosteneffizienten Kohlendioxidminderung beitragen, die erforderlich ist, um die globale Erwärmung unter 2 Grad Celsius zu halten. Um die größten Auswirkungen auf die Senkung der globalen Temperaturen zu erzielen, muss NbS jedoch jetzt ausgeweitet und langfristig angelegt werden. Die Einführung von NbS verläuft jedoch weiterhin schleppend, und es besteht nach wie vor eine deutliche Kluft zwischen den langsamen Maßnahmen in großem Maßstab und den vielversprechenden Forschungsergebnissen und politischen Aussagen. Dies zeigt, dass es dringend notwendig ist, die Umsetzungsbedingungen für NbS besser zu verstehen. Derzeit ist die Evidenzbasis zu NbS noch unvollständig, insbesondere wenn es um die systematische Bewertung der Wirksamkeit und der Umsetzungsanforderungen geht. Insbesondere fehlen bei groß angelegten Bewertungen wichtige kontextbezogene Informationen über Kultur, Verhalten und andere soziale und institutionelle Faktoren. Auch die vielfältigen Vorteile von NbS werden nach wie vor unterschätzt oder in einigen Fällen überhaupt nicht gewürdigt. Ziel dieser Arbeit ist es daher, politikrelevante Forschung zu betreiben, die dazu beitragen kann, die Lücke zwischen dem großen Potenzial naturbasierter Lösungen zur Bewältigung globaler Herausforderungen, insbesondere der Eindämmung des Klimawandels, und der langsamen Umsetzung in der Praxis zu schließen. Ausgehend von der vorhandenen Literatur zu NbS argumentiere ich, dass drei Bausteine für die erfolgreiche Umsetzung jeder NbS-Aktivität, insbesondere in großem Maßstab, wesentlich sind: (1) Wissenssynthese; (2) Planung und Entscheidungsfindung; (3) Politik und Finanzierungsmechanismen (**Abbildung A**, Seite ii). In dieser Arbeit untersuche ich diese Bereiche, indem ich Nachweise und Überlegungen zu theoretischen und methodischen Lücken in ihrer Bewertung sowie neue Perspektiven beisteuere. Dies tue ich auf drei Arten. Erstens werte ich systematisch die Literatur zu den Faktoren, die NCS ermöglichen, aus. Dabei hebe ich die Rolle der Synthese hervor, um zu verstehen, wie normative Annahmen und Narrative geformt werden, und um Lücken zu identifizieren, die zu Ungleichgewichten und mangelnder Repräsentation in Entscheidungsprozessen führen können. Zweitens erweitere ich meine Erkenntnisse aus der systematischen Literaturarbeit, die auf die Bedeutung sozialer Faktoren hinweisen, und untersuche

Ansatzpunkte für die Integration sozialer Aspekte in computergestützte Modelle (IAMs) für NbS, die hohe Sichtbarkeit an der Schnittstelle zur Politik genießen. Dadurch eröffne ich neue Perspektiven für den Diskurs über die Frage, warum die Sozialwissenschaften in IAMs unterrepräsentiert sind und wie dem begegnet werden kann, u. a. durch die Einbeziehung von Interessengruppen. Abschließend gehe ich auf eine Art von NbS ein - Waldaktivitäten - und stelle einen neuen theoretischen Rahmen für die Erfassung des aktuellen und zukünftigen Wertes von Wald-Co-Benefits vor. Dieser Rahmen baut auf der bestehenden theoretischen Literatur auf und bietet eine Grundlage für die Anwendung in natürlichen Ökosystemen außerhalb der Wälder. Meine Ergebnisse machen deutlich, dass die Umsetzung von NbS angesichts der komplexen und vielschichtigen Herausforderungen vor Ort eine ganzheitliche und interdisziplinäre Betrachtungsweise erfordert. Zukünftige Forschungsansätze sollten den Einsatz systematischer Methoden verfeinern und ausweiten, um bewährte Praktiken und Lehren für die Umsetzung umfassend zu bewerten und die Auswirkungen von NbS auf einen gerechten Übergang zu einer grünen Wirtschaft, einschließlich der Kompromisse und Nebeneffekte, zu vertiefen.

Contents

List of Figures

List of Tables

List of Abbreviations

ABM	Agent-based model
AFOLU	Agriculture, Forestry, and Other Land Use
ART	Architecture for REDD+ Transactions
BMU	Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety
CAR	Climate Action Reserve
CCQI	Carbon Credit Quality Initiative
CDM	Clean Development Mechanism
CDR	Carbon dioxide removal
CFBEM	Cloud Forest Blue Energy Mechanism
CO2	Carbon dioxide
COP26	26th Climate Change Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CWON	Changing Wealth of Nations
DRC	Democratic Republic of Congo
EA	East Asia
EKC	Environmental Kuznets Curve
ER	Emission reduction
ESM	Ecosystems Services and Management
EU	European Union
EUR	Europe
FAO	Food and Agriculture Organization of the United Nations
FPIC	Free, prior, and informed consent
GCAM	Global Change Assessment Model
GLOBIOM	Global Biosphere Management Model
GLP	Global Land Programme
HiAP	Health in All Policies
IAM	Integrated assessment model
ICJ	International Court of Justice
ICVCM	Integrity Council for the Voluntary Carbon Market

IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPLC	Indigenous peoples and local communities
IRI THESys	Integrative Research Institute on Transformations of Human-Environment Systems
IUCN	International Union for Conservation of Nature
JREDD+	Jurisdictional REDD+
LATAM	Latin America and the Caribbean
MACC	Marginal abatement cost curve
MCC	Mercator Research Institute on Global Commons and Climate Change
MEA	Millennium Ecosystem Assessment
MENA	Middle East and North Africa
MESSAGE	Model of Energy Supply Systems And their General Environmental Impact
MRV	Monitoring, reporting, and verification
NA	North America
NbS	Nature-based solutions
NCP	Nature's contributions to people
NCS	Natural climate solutions
NDC	Nationally Determined Contribution
NORAD	Norwegian Aid Agency
NYDF	New York Declaration of Forests
OC	Oceania
PES	Payments for ecosystem services
REDD+	Reducing Emissions from Deforestation and forest Degradation, as well as the sustainable management of forests and the conservation and enhancement of forest carbon stocks in developing countries
SA	South Asia
SBTi	Science Based Targets initiative
SCC	Social cost of carbon
SCD	Social cost of deforestation
SDG	Sustainable Development Goal
SEA	Southeast Asia
SESF	Socio-ecological systems framework
SRCCL	Special Report on Climate Change and Land
SSA	Sub-Saharan Africa
SSP	Shared socio-economic pathway

TEEB	The Economics of Ecosystems and Biodiversity
TEV	Total economic value
TNFD	Taskforce for Nature-related Financial Disclosures
TREES	The REDD+ Environmental Excellence Standard
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VCM	Voluntary carbon market
VCS	Verified Carbon Standard
WWF	World Wildlife Fund
YSSP	Young Scientists Summer Program

"it is necessary, while formulating the problems of which in
our further advance we are to find the solutions, to call into
council the views of those of our predecessors who have declared
any opinion on this subject, in order that we may profit by
whatever is sound in their suggestions and avoid their errors"

Aristotle, *De Anima*

Quoted in *The Handbook of Research Synthesis and Meta-Analysis*
(Cooper et al., 1994)

I. INTRODUCTION

I.1 The potential of nature-based solutions

Societies today are being faced with unprecedented social, ecological, political, and economic challenges (Donatti et al., 2022). These complex and interlinked challenges are largely the result of human interventions on the Earth (Steffen et al., 2015). Furthermore, global environmental changes, such as shifting land use and earth system dynamics, are exacerbating these challenges and effects on nature and people around the world (IPCC, 2022; Pörtner et al., 2021). For example, exposure of a community to heatwaves has impacts on health, nutrition, and food security (McMichael et al., 2015; Romanello et al., 2022); changing, and declining, access to resources is a catalyst for human displacement (Lunstrum & Bose, 2022); and global warming is expected to amplify the frequency of weather events like extreme precipitation and flooding (Tabari, 2020).

The concept of *nature-based solutions* (NbS) emerged to give a term to the range of activities and approaches that learn from and work in and with nature to address these global societal challenges (Cohen-Shacham et al., 2016). When it comes to some of the most pressing challenges – the mitigation and adaptation to climate change, protection of biodiversity, and improvement of human well-being – NbS have the potential to tackle them while providing multiple additional benefits (Donatti et al., 2022; Seddon et al., 2020). To give two examples: When farmers plant native trees, they are diversifying their sources of income while increasing soil organic carbon and aboveground biomass (Augusto & Boča, 2022). Similarly, conservation areas not only enhance ecological function and resilience, but are also habitats for diverse species and can provide spaces for recreation, community building, and establishing social cohesion (Kowarik & Langer, 2005).

Recent years have seen increased excitement and media attention around the role nature can play in climate change mitigation and adaptation in particular, bolstered in 2021 by the beginning of the United Nation's Decade of Restoration and the emphasis on nature at the 26th Climate Change Conference of the Parties (COP26). Many countries include different types of NbS as a part of their Nationally Determined Contributions (NDCs), which are climate action plans under the Paris Agreement (Seddon et al., 2019). High-level, multi-stakeholder initiatives such as the Bonn Challenge and New York Declaration on Forests also recognize the close ties to NbS (Donatti et al., 2022). In addition, large-scale modelling projections, such as those that inform the United Nation's Intergovernmental Panel on Climate Change (IPCC), highlight nature-based approaches to carbon removal as integral to meeting global temperature targets (IPCC, 2022). These approaches, which are also captured under what the IPCC refers to as *land-based mitigation measures*, include activities such as afforestation, reforestation, improved forest management, agroforestry, and soil carbon sequestration.

Specific estimates of the technical mitigation potential of nature-based solutions for climate change mitigation also point to substantial biophysical and carbon benefits. Griscom et al. (2017), for instance, find that *natural climate solutions* (NCS) – a subset of NbS that focuses on the protection and enhancement of natural ecosystems to improve carbon sequestration[1] – can provide over a third (37%) of the cost-effective carbon dioxide (CO2) mitigation needed through 2030 to hold global warming to below 2 degrees Celsius (23.8 gigatonnes of CO2 equivalent per year). Roe et al. (2019) likewise estimate that measures in the land sector can contribute about 30% of what is needed to meet the 1.5-degree target by 2050 (15 gigatonnes of CO2 equivalent per year)[2]. Importantly, Girardin et al. (2021) also show that NbS contribute to cooling the planet after peak warming, most significantly in a 2-degree scenario. However, the mitigation potential ranges in the assessments these studies are based on are large and there is a lack of integrated studies on NbS and NCS. As such, many estimates of the mitigation potential include large uncertainties, optimistic assumptions, and lack quality information on barriers to implementation and ecological constraints, likely resulting in an overestimation of the realistic potential (Reise et al., 2022).

In addition, meeting the mitigation potential and increased climate ambition that can be achieved through NbS requires that certain conditions are in place. These conditions include comprehensive governance frameworks, dedicated budgets for activities, and engagement of stakeholders that values different types of knowledge (Nelson et al., 2020; Pérez-Cirera et al., 2021). NbS are also not a cure-all solution, and decisions will have to be made that may result in trade-offs (Seddon et al., 2020). As such, a better understanding of the evidence is essential to make informed choices that consider multiple options, and to minimize negative outcomes. Finally, NbS must be implemented together with rapid decarbonization if we are to meet global temperature targets (Anderson et al., 2019; Girardin et al., 2021). Delaying emissions reductions in other sectors, such as energy and industry, will only result in greater cumulative emissions and peak warming in the long run (Anderson et al., 2019). NbS may also be adversely affected by changes in ecosystem functions that occur due to global warming and extreme climate events, impacting their effectiveness of NbS (Girardin et al., 2021). Critically, this increases the risk of inducing potentially irreversible changes to the Earth system, also known as climate tipping points.

[1] An important difference between natural climate solutions (NCS) and nature-based solutions (NbS), beyond the primary climate and carbon framing of NCS, is that NCS focuses on natural ecosystems and NbS includes natural, modified, and built ecosystems (see **Chapter IV.1** for full definitions and further discussion).
[2] Some activities included in Griscom et al. (2017) and Roe et al. (2019) fall outside the scope of NbS because they do not meet the principles that outline what qualifies as NbS (see **Chapter II.1**). These include, for example, addressing enteric fermentation and manure management.

I.2 Nature-based solutions in practice

Despite strong support for NbS, uptake remains slow (Chee et al., 2021; Sarabi et al., 2019). According to the Intergovernmental Panel on Climate Change special report on global warming to 1.5 degrees Celsius, "the implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological, financing and environmental barriers that differ across regions" (IPCC, 2018). These barriers range from disagreement on the definition of NbS, NCS, and related terms to lack of public awareness and support, with many others in between (Håkanson, 2021; Sarabi et al., 2019).

While there are political signals driving the importance of NbS, these have not yet been fully reflected in policy or action at scale (Reise et al., 2022). The European Union (EU), for example, was an early adopter of the term and has funded large research programs on NbS via the European Commission (Mendes et al., 2020). Though NbS terminology has not been used in EU strategy documents, many include NbS components (Davies et al., 2021). The Roadmap to a Resource Efficient Europe, for example, discusses the role of natural capital and ecosystem services for a sustainable economy (EU Commission, 2011). Similarly, the EU's Action Plan on the Sendai Framework acknowledges opportunities for NbS to contribute to ecosystem-based disaster reduction and adaptation to climate change in the future (EU Commission, 2016).

Predecessors and early policies in the realm of NbS also experienced many mistakes. The Clean Development Mechanism (CDM) had mixed outcomes and was full of projects that did not deliver on promised benefits, both to sustainable development and climate change mitigation (Kneteman & Green, 2009). On the one hand, a case study on a CDM project in Uganda reveals multiple compounding failures, including limited engagement of stakeholders, which was tied to poor communication and distrust, and weak institutional capacity (Aganyira et al., 2019). On the other hand, a project in Ethiopia demonstrates a more successful approach to drive environmental restoration and income generation by building a foundation for community ownership by establishing cooperatives and securing land rights for participants (Brown et al., 2011).

Lessons from the evolution of the 'Reducing Emissions from Deforestation and forest Degradation, as well as the sustainable management of forests and the conservation and enhancement of forest carbon stocks in developing countries' (REDD+) framework also provide useful insights, as well as highlight room for improvement. Critics point to the contestation of REDD+ by some indigenous peoples and local communities and concerns about the integrity of activities due to uncertain measurement and baseline setting approaches (Asiyanbi & Lund, 2020; Huettner, 2012; West et al., 2020). Similar to CDM, lack of capacity for implementation remains a major challenge to REDD+ in many countries (Poudel et al., 2022). Gaps also often remain in compliance and enforcement, for example when it comes to regulating land use for commercial purposes (Ankomah et al., 2022). There are advancements, however. The growth of subnational, jurisdictional REDD+ programs is one major example. These programs aim to take a more holistic, multisectoral view of a landscape with the intention of designing policies that integrate different objectives and stakeholder perspectives (Wunder et al., 2020).

Recognizing the urgent need for progress, academic and policy debates have largely shifted towards questions of implementation and feasibility. This is not unfounded, as to see the most benefits from nature-based solutions, the sooner implementation happens, the better. Furthermore, to have the biggest effect on reducing global temperatures, NbS must be scaled up now and designed for the long-term (Girardin et al., 2021; Moallemi et al., 2022). Yet, we still have a long way to go. Humans have already altered nearly three-quarters of terrestrial environments (IPBES, 2019). Nature is changing at unprecedented rates, accelerating species extinction and biodiversity loss. Finally, limited progress has been made towards meeting the SDGs, and it is unlikely that the 2030 targets will be met (Moallemi et al., 2022).

I.3 Research gap & problem definition

There remains a clear gap between the action on NbS and the promising research and policy narratives (IPBES, 2022; IPCC, 2019). This raises several overarching questions, which motivate this thesis. What is the reason for this action-research gap? What is missing from the research, or not being taken into account? How is research translated into policy? Is the research useful for policymakers? What are the assumptions and evidence that are informing these narratives? How can we best leverage available evidence and knowledge to advance NbS implementation?

In addition, when it comes to climate change mitigation, understanding which natural climate solutions pathways have the most opportunity to overcome implementation barriers and where would provide a crucial step to accelerate implementation and for stakeholders to be able to provide more targeted and strategic support for NCS activities. This is important to note as, in addition to the potential co-benefits, NCS may provide a better immediate entry point for mitigation action than other potential options. For example, other carbon dioxide removal (CDR) technologies (e.g., bioenergy combined with carbon capture and storage, direct air capture, or solar radiation modification) have been highly controversial due to concerns about ethics, geological storage, and uncertain impacts (Fuss et al., 2018; Honegger et al., 2022; Lenzi et al., 2018; Minx et al., 2018; Reynolds, 2018). Many countries are also currently unprepared for deployment of a broad suite of CDR options at scale. This is illustrated by a recent report on the EU, which found that no Member State has a dedicated or comprehensive CDR strategy and few of the existing regulations on CDR include non-nature-based options (Meyer-Ohlendorf & Spasova, 2022).

Given the pressing questions facing societies today, many governments are looking to researchers to provide them information that can support them in making informed policy decisions; and many research communities are expanding their priorities to include the identification of evidence needs and creation of robust, comprehensive evidence bases. Yet, exploding amounts of literature – in particular in the field of climate change – make it difficult for scientific assessments and researchers to keep up (Callaghan et al., 2020; Minx et al., 2017). Furthermore, research on NbS in practice has to date consisted of scattered case studies or reviews and evidence synthesis focusing on specific NbS activities or regions (Chausson et al., 2020). Many of these studies are incomparable and context-specific. While this is relevant to policymaking at the local level, it makes it challenging to incorporate important information from the social sciences into large-scale research in a robust and meaningful way (Minx et al., 2017). Studies on NbS are also often buried in the literature across different disciplines, which makes it difficult for researchers and policymakers alike to find and access information.

Both the overwhelming amount of literature and the inability to navigate it carry significant risks, such as perpetuating a lack of representation and selection bias in high-level processes (Callaghan et al., 2020). It is important to proactively address these risks to avoid misinforming future funding streams and policy narratives, and in turn future research and knowledge production. Bearing this in mind, **four specific research gaps serve as entry points** for the work in this thesis:

- First, there is **limited evidence synthesis** on NbS. The evidence base on NbS remains incomplete, especially when it comes to effectiveness and requirements for implementation (Cheng et al., 2022; Kabisch et al., 2016). A number of studies explore barriers to implementation and present frameworks for assessing and implementing NbS (Albert et al., 2019; Cohen-Shacham et al., 2019; Raymond et al., 2017; Wickenberg et al., 2021). Yet, few apply these frameworks broadly and none assess the current evidence systematically and comprehensively. In addition, syntheses of NCS focus primarily on specific activities or regions (Cheng et al., 2022).
- Second, **social sciences are underrepresented** in high-level research on the environment, climate, and sustainability (Shrivastava et al., 2020; Victor, 2015). There is a need for more integrated research that can account for different perspectives. In particular, important contextual information on culture, behavior, and other social and institutional dynamics are lacking. This gap in the knowledge production processes that inform influential decision-making processes is one underlying reason why policies continue to be ineffective and slow progress has been made in addressing global challenges (Mead, 2015; Newman & Head, 2015).
- Third, the **mechanisms for unlocking NbS are lagging**. There is a significant gap when it comes to financing NbS, for example. Almost four times more investment will be needed by 2050 if current global climate change, biodiversity and land degradation targets are to be met (UNEP, 2021b). Currently, the majority of finance for NbS is publicly sourced and there is a need to leverage more private finance. There remains, however, confusion around the risks and opportunities for doing so.

- Last, **few analyses value the multiple benefits of NbS**. While they are certainly recognized and becoming more prevalent in policy dialogues, research tends to focus on individual services that NbS can provide, rather than holistic evaluations (Mengist & Soromessa, 2019). Furthermore, it is unclear how these benefits are currently valued and considered in policy and financing mechanisms. While there are many technical challenges to valuations of benefits, not valuing them is also not an option, as this essentially makes their value equivalent to zero (Druckenmiller, 2022).

The **Conceptual Framework** section (**Chapter II**) elaborates on these gaps and puts them into the broader NbS and geographical research context.

I.4 Objective, contribution, & scope

The objective of this thesis is **to conduct policy-relevant research** that can contribute to closing **the gap between the high potential for nature-based solutions to address global challenges**, particularly climate change mitigation, **and the realities of slow implementation in practice.**

Drawing on the existing literature on NbS, I argue that three building blocks are essential to driving successful implementation of any NbS activity, in particular at scale: (1) knowledge synthesis; (2) planning & decision-making; (3) policy & financing mechanisms (see **Chapter, II.3**; Bowen & Zwi, 2005; Jann & Wegrich, 2006; Pérez-Cirera et al., 2021). These are influenced by dynamic factors such as governance contexts and collaborative processes. As such, I explore these three building blocks within this thesis and contribute evidence and reflection on theoretical and methodological gaps in their assessment, as well as new and innovative perspectives.

I do this by undertaking four independent, but related, studies that focus on different research gaps and aspects of implementation. The studies all use nature-based solutions as a framing, emphasizing climate change mitigation as an objective as this has been at the forefront of national and international agendas. At the same time, the studies vary in scope. This allows me to start broad and observe existing evidence to draw new insights in some studies, but also zoom in on specific issues in others. Taken together, the results of this research can aid in developing more comprehensive strategies for NbS implementation. To give an **overview of the studies**:

- The first study, titled "What influences the implementation of natural climate solutions? A systematic map and review of the evidence," contributes to addressing the gap of the **limited evidence synthesis** on NbS (**Chapter IV.1**; Schulte et al., 2022). I focus on NCS for methodological and pragmatic reasons, and because of my interest in the climate angle. In the study, I highlight **the role of knowledge synthesis in understanding how normative assumptions and narratives are shaped** and where there may be research gaps that risk leading to imbalances and lack of representation in high-level processes that are informed by such research. I demonstrate this by undertaking a knowledge synthesis exercise of my own, a systematic review that takes stock of the evidence available on enabling factors that influence the implementation of natural climate solutions.

- The second study, titled "Towards integration? Considering social aspects with large-scale computational models for nature-based solutions," contributes new perspectives on the discourse about why the **social sciences are underrepresented** in high-level research (**Chapter IV.2**; Schulte et al., in review-b). Specifically, I focus on large-scale land-use and integrated assessment models (IAMs) and explore **how they can be improved by complementing them with social science research**, since they are important to informing planning and decision-making processes. A critique of current models is that they lack realism and hold large uncertainties (Beck & Krueger, 2016; Pindyck, 2017; Riahi et al., 2015). Leveraging extensive literature review and interviews with experts, I identify entry points for better integration of models and social sciences.
- The third study, titled "Valuing the hidden benefits of forest-based climate change mitigation" builds on the gaps that **mechanisms for unlocking NbS are lagging** and **few analyses value the multiple benefits of NbS** (**Chapter IV.3**; Schulte et al., in review-a). This study looks at one category of NCS – forests activities – and proposes strategies to capture the full value of co-benefits. It also presents a new theoretical framework for considering this value, recognizing it in policy, and leveraging it to potentially identify more channels for finance. I focus on forests because – based on our findings in Schulte et al. (2022) – this is the land-type most research on NCS activities is on, and thus that is where the most evidence is available. Lessons from the study are widely applicable to other ecosystems, however.

Overall, the outcomes of this research provide a valuable contribution to science and policy. Currently, NbS research that bridges the evidence-policy divide is limited. Furthermore, better research on NbS is needed, particularly as the field expands into marine and other ecosystems. As this thesis comments on the research process itself, it also contributes to enhancing and developing methods and theories that can advance ways of learning and knowing about NbS.

I.5 Statement on the chapters of the thesis

This thesis consists of five chapters. **Chapters I-III** introduce the conceptual, epistemological, and methodological background of my work. **Chapter IV** is heart of the thesis and presents the outputs of four years of dedicated research on NbS. **Chapter V** brings together the different chapters and concludes this thesis. Each is chapter is summarized below.

Chapter I: Introduction provides initial remarks on the topic of nature-based solutions and sets the stage for the remainder of this thesis. It describes the motivation and objective of the thesis, as well as the problem and research gaps I aim to contribute to.

Chapter II: Conceptual Framework outlines concepts and definitions relevant to this thesis, places it within the field of Geography, and illustrates how my how the content of this thesis contributes to my objective of conducting policy-relevant research and NbS implementation.

Chapter III: Methodological Framework describes my research process, including the development of my research approach, the methodological principles guiding my work, and the research methods I engage with. I also comment on the limitations of this thesis.

Chapter IV: Research Outputs presents the core research undertaken for this thesis. The thesis is a so-called cumulative thesis, meaning it is based on four paper manuscripts either published or under revision. While the papers are closely interconnected, they each comprise a standalone subsection, thus dividing the chapter into three subsections. Each sub-chapter responds to a different aspect of the overall thesis objective (see **Chapter I.4**). The citation and author contributions for each manuscript are:

- **Chapter IV.1: What influences the implementation of natural climate solutions? A systematic map and review of the evidence**

  Schulte I., Eggers J., Nielsen J.Ø., Fuss S. (2022). What influences the implementation of natural climate solutions? A systematic map and review of the evidence. *Environmental Research Letters*, *17*(013002).

  IS conceived of the study. **IS**, SF, and JE screened and coded the papers in the study. **IS** performed the analysis, formulated the figures, and wrote the manuscript. **IS**, SF, and JON discussed the results and contributed to the final manuscript. SF supervised the project.

- **Chapter IV.2: Towards integration? Considering social aspects with large-scale computational models for nature-based solutions**

  Schulte, I., Yowargana, P., Nielsen J.Ø., Kraxner, F., Fuss, S. Towards integration? Considering social aspects with large-scale computational models for nature-based solutions. In review at *Global Sustainability.*

  IS, PY, FK, and SF conceived of the study. **IS**, PY, JON, and SF developed the methodology. **IS** performed the research, analysis, wrote, and revised the manuscript. PY contributed to analysis and writing. **IS**, PY, JON, FK, and SF discussed the results of the research. PY, JON, FK, and SF provided review and revision on drafts of the manuscript. PY and SF supervised the project.

- **Chapter IV.3: Valuing the hidden benefits of forest-based climate change mitigation**

  Schulte, I., Golub, A. Gerbode, C., Dockendorff, C., Fuss, S. Valuing the hidden benefits of forest-based climate change mitigation. In review at *One Earth*.

  SF, AG, and CD conceived of the study. **IS**, AG, CG, CD, and SF conceptualized the research. AG led the development of the theoretical framework. **IS** led the research, development, and writing of the manuscript. All co-authors contributed to the development of the theoretical framework and manuscript, including research, writing, and editing. IS led the reviewing and editing process. SF supervised the project.

Chapter V: Conclusion synthesizes the main findings and takeaways of this thesis. Additionally, I reflect on future research directions and potential policy implications of my work.

II. CONCEPTUAL FRAMEWORK

II.1 The dynamic evolution of NbS

A short history of NbS

Notions of working with(in) nature and holistic practices surrounding nature and the management of its resources have been around for centuries (Cassin & Ochoa-Tocachi, 2021). Indigenous and local communities have long-standing traditional ways of learning, knowing, and interacting with their surroundings, undertaking activities that Western scientists might categorize as integrated ecosystem management or adaptive learning management practices, self-monitoring for conservation, and community monitoring of environmental change based on signs and signals in the lands they interact with (Berkes, 2009). Traditional agroecological systems may utilize elements like trenches, terraces, and irrigation channels but also social factors that affect the rules and maintenance of the system. As such, the system itself consists of numerous processes and relations that impact the surrounding ecosystem functions. The functions include soil nutrients, vegetation, and biodiversity, among many others (Altieri, 2019).

In the Philippines, for example, the 400-year old rice terraces of the Ifugao are seen as a resilient socio-ecological system, relying on the close relationship of Ifugao traditional practices and social order with the landscape (Acabado, 2018; Araral, 2013). The terraces, still currently in use, are a part of a larger, integrated system that includes intercropping and agroforestry alongside the fundamental community-managed irrigation system and cultural values that drive social cohesion. In Peru, researchers are exploring the potential of indigenous water infiltration enhancement, like the 1,400-year-old pre-Inca Huamantanga system, to contribute to water security in the Andes (Ochoa-Tocachi et al., 2019).

The idea of "designing with nature" has also been a touchstone of urban planners and landscape architects since at least the 18th century (Cassin, 2021; McHarg, 1969). This is exemplified through the work of Frederick Law Olmsted and his belief that bringing nature back into cities had important benefits for human physical and mental health and well-being, in addition to promoting community and shared values (Eisenman, 2013). His design of the Emerald Necklace (1878-1896), a connection of 1100 acres of parks and waterways in Boston, is an early demonstration of what we today might call *blue-green infrastructure*[3] (Emerald Necklace Conservancy, 2022).

[3] *Blue-green infrastructure* falls under the *NbS* concept. It can include natural and modified green spaces and water systems.

In the late 2000s, faced with increasing concerns about unsustainable development and resource use, as well as renewed interest in approaches to development that consider the role of ecosystems, a new term emerged: *nature-based solutions* (Cassin, 2021; Seddon et al., 2021). *NbS* has often been used as a catch-all term for categorizing approaches and interventions in and inspired by nature – such as natural systems and processes – that address societal challenges (Anderson & Gough, 2022; Seddon et al., 2021). Nevertheless, an important component of the NbS concept is the recognition of reciprocal relationships between people and nature, consisting of complex interactions and feedback loops (Seddon et al., 2019).

The first reference to the term *nature-based solutions* dates back to the title of a World Bank (2008) report that argued that "the conservation and sustainable use of natural ecosystems and biodiversity are critical to fulfilling [their] objectives [to alleviate poverty and support sustainable development]." While the report did not provide a definition of NbS, it summarized 20 years of World Bank Group projects supporting biodiversity and sustainable use in different natural habitats, highlighting the cross-cutting impacts of those projects on the environment, climate change, and human livelihoods. In subsequent years, various organizations expanded on the concept, developing more specific definitions and frameworks. Multiple definitions of NbS now exist from non-governmental organizations, businesses, and multilateral organizations alike, many of which are individualized but similar (**Table 1**).

Table 1. Examples of definitions of NbS

Organization	Definition
European Commission (EU Commission, 2023)	"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"
International Union for Conservation of Nature (Cohen-Shacham et al., 2016)	"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"
Nature-based Solutions initiative (NbSi, 2023)	"Actions that involve the protection, restoration or management of natural and semi-natural ecosystems; the sustainable management of aquatic systems and working lands such as croplands or timberlands; or the creation of novel ecosystems in and around cities. They are actions that are underpinned by biodiversity and are designed and implemented with the full engagement and consent of local communities and Indigenous Peoples"
World Economic Forum (WEF, 2021)	"A collection of actions and policies that harness the power of nature to protect and restore ecosystems while addressing societal challenges to simultaneously safeguard human well-being and biodiversity"
World Wildlife Fund for Nature (WWF, 2022)	"Harness the power of nature to boost natural ecosystems, biodiversity and human well-being to address major societal issues, including climate change"

In 2016, for example, the International Union for Conservation of Nature (IUCN) published a report taking steps to provide operational clarity on the concept (Cohen-Shacham et al., 2016). They define NbS 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." The European Commission definition, however, has a slightly different focus, calling NbS "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" (EU Commission, 2023).

NbS in present day

There is a rapidly increasing literature body on nature-based solutions. Hanson et al. (2020) found 112 retrievable peer-reviewed articles or reviews in Web of Science and Scopus with the term *nature-based solutions* that were published up to May 2018. Most study authors were based at universities or research institutes, but many studies also included authors from other organizations. Two years later, Seddon et al. (2020) conducted the same search and received 648 results – nearly six times more. They note, however, that the relevant literature is likely much larger. In March 2023, I conducted a similar search on just the Scopus platform, where the exponential growth trend continues to be evident (**Figure 1**).

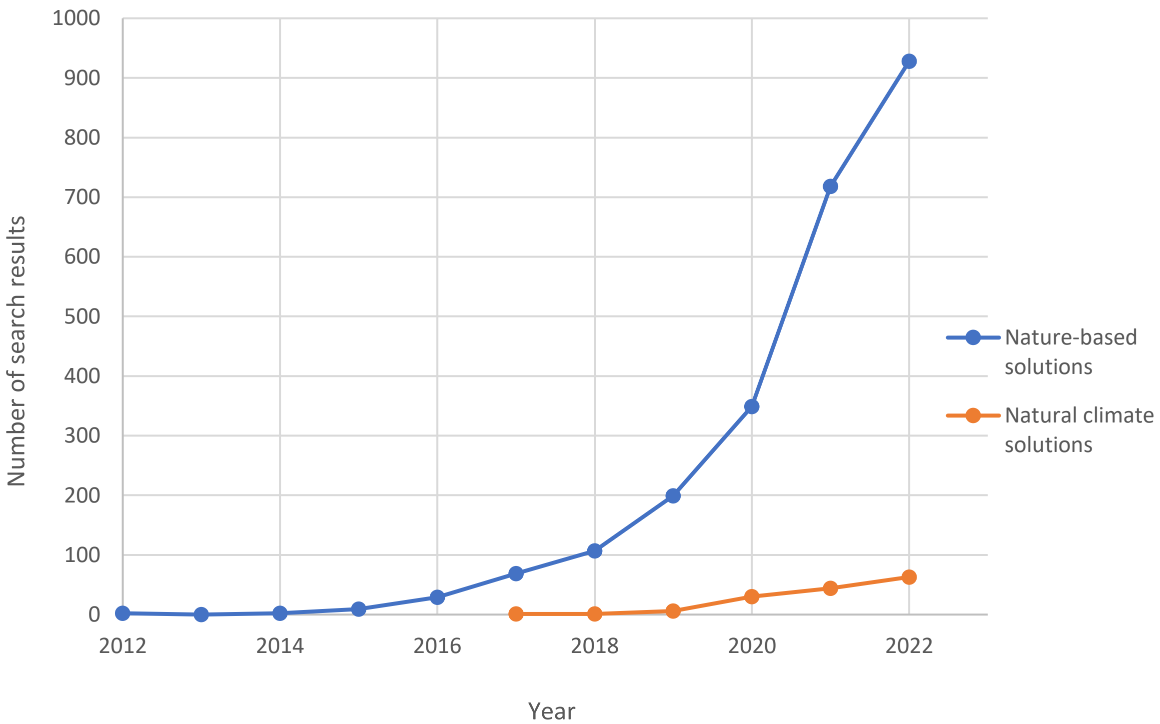

Figure 1. Number of Scopus search results for the terms NbS and NCS.

It is also interesting to view these results in comparison to the number of results with the term *natural climate solutions*, which have remained relatively lower and stagnated. This is partially due to the fact that NCS has a more nuanced definition and thus a smaller set of activities that qualify. Similar to NbS, however, there is significant literature on activities that could qualify as NCS but do not use the term. I expand on this discussion in **Chapter IV.1**. NCS also was a term that received a lot of attention when it first appeared. Since then, there has been ongoing discussion about the terms NbS and NCS and their relationship, which has also changed over time. This can be seen in different terminology from the last few years that tries to bring the two together such as *nature-based solutions for climate change mitigation* and *nature-based climate solutions* (Nolan et al., 2021; UNEP, 2021a). It is also possible that study authors are placing precedent on NbS over NCS when it comes to terminology, since it is more all-encompassing, and thus the number of papers mentioning NCS has plateaued.

This trend in the literature is one of many indications that the term *nature-based solutions* has become popular with practitioners, as well as researchers who aim to bridge the science-policy divide (Anderson & Gough, 2022). This increase in traction may be in part due to the accessibility and flexibility of the concept. At the same time, the lack of specific metrics for determining what qualifies as a NbS has led to conceptual fuzziness and concerns about greenwashing (Nature, 2017; Nesshöver et al., 2017). The term was notably removed from the final text of the Glasgow Climate Pact, though the role of nature in meeting global temperature targets was recognized, illustrating the tension surrounding the concept in practice (Carbon Brief, 2021).

On the one hand, there is value to the vagueness, as it has allowed NbS to be a unifying concept and bring together different disciplines and actors. On the other hand, turning the ideas of NbS into implementable actions requires more granular thinking that is targeted to different sectors, ecosystems, and geographies. As such, in 2020 the International Union for the Conservation of Nature published a global standard for nature-based solutions. The standard builds on a set of previously published core principles and consists of eight criteria and accompanying indicators, as well as guidance for the design, verification, and scaling up of NbS (Cohen-Shacham et al., 2019; IUCN, 2020). Other environmental organizations, such as the World Wildlife Fund (WWF), encourage the use of this standard. In addition, a number of initiatives have been created around the globe that are dedicated to fostering dialogue and research on nature-based solutions and natural climate solutions. These include the Nature4Climate, a coalition of 20 organizations across the environmental sector; the Natural Climate Solutions Alliance, convened by the World Business Council for Sustainable Development and World Economic Forum; and academic efforts such as the Massachusetts Institute of Technology Natural Climate Solutions Program, the National University of Singapore Centre for Nature-based Climate Solutions, the Yale FedEx Center for Natural Carbon Capture, and the Oxford University Nature-based Solutions initiative.

The establishment of the standard and other efforts to advance knowledge on NbS highlight the current focus on defining "legitimate" NbS (NbSi, 2022). It is clear that NbS is seen by many people as a positive force for addressing climate change, but also potentially a dangerous distraction unless concerns about what is considered "good" NbS are meaningfully addressed. In a landmark decision, the United Nations Environment Assembly (UNEA) made a resolution on *Nature-based Solutions for supporting sustainable development*. The resolution adopts a mutually agreed on definition of NbS and recognizes the importance of having a well-defined concept to avoid misuse (UNEP, 2022a). This sentiment was reiterated by Inger Andersen, Executive Director of the United Nations Environment Programme (UNEP), who noted that "having a universally agreed definition of Nature-based Solutions is important. When countries and companies claim that their actions are supporting Nature-based Solutions, we can now begin to assess whether this is accurate and what it entails" (UNEP, 2022b).

II.2 Research in the field of geography

The origins and struggles of geography

Geography has always been a dynamic field. Originally stemming from geology, the study of physical geography gained momentum in the late 19th century, eventually becoming its own subject and expanding to include the realm of human geography (Smith, 1987). Recovery from World War II drove interest in geography as a subject for learning about world affairs, and a demand for trained geographers. This broadening into more social and political forms of geography, however, was also a driver of tension within academic institutions. Since the 1940s, the field of geography has been experiencing an "academic war" (Lahiri-Dutt, 2019; Smith, 1987). Notably, Harvard University terminated its geography program in 1948, catalyzing discussions about the vulnerability of the discipline and questioning its relevance.

In the early 1960s, Barry N. Floyd summarized the deluge of new comments, concepts, and definitions in geography that were appearing, calling them "Geographical Gleanings" (Floyd, 1963). I have updated his selection with a few of my own, drawn from the circles my work occupies and interacts with (**Table 2**). Following Floyd's publication, William D. Pattison (1964) presented an alternative view of geography, to better communicate the work of geographers. Pattison's view is framed by four traditions of geography, rather than the adoption of any one definition: a spatial tradition, an area studies tradition, a man[sic]-land tradition, and an earth science tradition.

Pattison's spatial tradition explores the boundaries, shapes, and distances of a place, usually identified through mapping exercises. The area studies tradition focuses on developing in-depth knowledge of a place and what makes it unique. The man[sic]-land tradition looks at the interactions between humans and the land they use and live on; what today's researchers would call human-environment relations. The earth science tradition is concerned with the physical aspects of geography, and planet Earth and its systems, like the atmosphere and biosphere. While his framework lacks in some areas – for example, he does not explain how he decided on these groups – he was the first to embrace multiple distinct orientations of geographical research without marginalizing others (Murphy, 2014).

Table 2. "Geographical Gleanings" (a selection of definitions from Floyd, 1963 and own research)

Writer	Comment on geography
Immanuel Kant	"History encompasses the unifying element of time, so Geography provides the unifying element of space"
Alfred Hettner	"Geography is the chronological science of the earth or the science of earth areas and places in terms of their differences and their spatial relations"
Association of American Geographers	"Geography is a form of general education like History, and together they provide the basic framework of place and period essential for understanding the social, political, and economic problems of the modern world"
UNESCO	"Geography consists in locating, describing, explaining and comparing scenery and human activities on the face of the globe"
Jean Bruhnes	"Modern Geography aims at the comparison and classification of phenomena and endeavors to explain these in the widest sense of the word "explain"
Geography Department, HU Berlin	"We understand geography as the discipline studying the interactions and feedbacks between people and their natural and built-up surroundings"
Cambridge Dictionary	"[Geography is] the study of the systems and processes involved in the world's weather, mountains, seas, lakes, etc. and of the ways in which countries and people organize life within an area"
National Geographic Society	"Geography is the study of places and the relationships between people and their environments. Geographers explore both the physical properties of Earth's surface and the human societies spread across it"
Royal Geographical Society	"Geography is unique in bridging the social sciences and natural sciences […] Geography provides an ideal framework for relating other fields of knowledge"

While the battles come in waves, there are constant reminders that the field of geography is still fighting for its place in academia. This is likely due in part to the identity struggles of the field, as well as the expanding breadth and diversity of the subjects within it. Many universities, for example, in the United States, no longer have geography departments (Frazier & Wikle, 2017). Around the world, geographers by training find themselves absorbed into other departments or in newly created or rebranded departments containing terms like Earth & Planetary Sciences, Sustainability Science, and Future Planet Studies, among others (Butler, 2010; Frazier & Wikle, 2017; Hudson & Hinman, 2017; Martin, 2018; Winkler, 2014).

At the same time, the ongoing reevaluation of the discipline provides an opportunity for turning inward and reflecting on its strengths. Geographers are valued for their contributions to interdisciplinary and international curricula, which are increasing in demand and importance in today's complex and globalized world (Frazier & Wikle, 2017; Hudson & Hinman, 2017). Similarly, the success and survival of geography departments to date, even those now called by a different name, can partially be attributed to their adaptability and collaborativeness (Hudson & Hinman, 2017; Knight, 2018; Miao et al., 2022). These characteristics of the field have seemingly ensured their continued relevance and visibility in changing institutional and real-world contexts.

Geography: A field for today's challenges

David S.G. Thomas, in a commentary published last year (2022), astutely makes the case that "geography needs science [and] science needs geography." I would agree with Thomas, who also argues that geography is particularly important to research on environmental challenges. Given the questions that face researchers today and in the future – in particular young researchers such as myself – the fluid, difficult to define nature of the discipline that was once seen as a weakness is arguably what makes it an appropriate venue for conducting cross-cutting research that requires "disciplinary agility."

So, what does this have to do with nature-based solutions? The designation of the Anthropocene, the unofficial epoch we find ourselves living in, marked a significant shift in discourse around the relationship between humans and the global environment (Lewis & Maslin, 2015). It introduced the idea that ways of thinking and conducting research could be "anthropocentric", or human-oriented. Simultaneously, the Anthropocene has become a framework for shedding light on many of the challenges our societies are facing today, such as climate change, growing inequality, and biodiversity loss, and considering how to shift our behaviors and transition towards a better future. The Sustainable Development Goals, set up by the United Nations General Assembly in 2015, in some ways formalize these societal challenges and lay out an idealized version of what this better future should look like. NbS are frequently presented as a possible cross-cutting solution that contributes to multiple SDGs, but they have also been criticized by some for being too anthropocentric (Maller, 2021). Nevertheless, others argue that the NbS concept makes clear that nature and humans cannot be separated and can open doors for 'more-than-human' thinking and planning in societies.

Already prior to the SDGs, practitioners, academics, and development organizations had identified a need for the research community to not only work on identifying problems of sustainability, but also to investigate practical solutions for these problems (Clark & Dickson, 2003). The result was a new area of research, sustainability science, which had and still has a wide-ranging agenda. It requires articulating and engaging with normative processes and perspectives (Nielsen et al., 2019). As such, the agenda has brought together scholarship and practice, as well as different perspectives and disciplines to understand the ways in which humans are reshaping nature-society systems. This is a core interest of geography, as well, making it a fitting home for these dialogues to converge.

We now have new communities of researchers working in areas such as global environmental change and land system science. These communities are brought together by common themes and questions, rather than shared disciplines or methods, recognizing that the questions can only be answered if we work in collaboration across knowledge domains, scales, and contexts (de Bremond et al., 2019). Nature-based solutions are one of these themes. Furthermore, due to the normativity inherent in the motivations for and questions being asked in research on nature-based solutions, NbS also serves as an entryway to the sustainability science interface and policymaking arena.

II.3 The relevance of geography for implementing NbS

Geography's intervention in public policy

In 1974, David Harvey asked "can geographers contribute successfully, meaningfully, and objectively to public policy?" To him, the two important questions researchers needed to reflect on were "what kind of geography and what kind of public policy?" (Harvey, 1974). He outlines several potential reasons why geographers may feel inclined to contribute to public policy to begin with, including personal ambition, disciplinary reputation, social necessity, and moral obligation. While these may shape the work of geographers, he expresses that geographers must also reflect and overcome the parochial, or narrow, views that may be brought about their individual situations, whether it be existing institutional structures or corporate states they work within. Instead, he advocates for geographers to embrace the inherent tensions that may arise from thinking critically and work towards informing a more progressive, incorporated state.

In practice, geography still struggled to be seen as a valuable discipline compared to other areas of social science, such as economics and health studies. In the early 2000s, politicians began expressing interest in 'evidence-based policy' – policy that is informed by high-quality, empirical data. In the United Kingdom, for example, the government explicitly called for closer exchange between policymakers and academics, in particular from the social sciences (James et al., 2004). Geography, however, was not referenced by politicians in these discussions about the social sciences. As such, the discipline of geography experienced a resurgence of debate regarding its role in research and the kinds of questions it seeks to answer. Concerns about the discipline's influence and weak image echoed observations already made two decades before by Dawson & Hebden (1984), who stated that "the public face of geography is of concern for its long-term survival." Ron Martin (2001), for example, notes that the impact of geography "on the public policy realm has in general been disappointingly limited." James et al. (2004), express similar sentiments, noting that geography may not be "punching its weight."

Martin (2001) goes on map a way forward for a 'policy turn' and movement towards a 'geography of public policy.' According to him reasons for the limitations included the discipline taking turns in other directions, towards postmodernist and cultural modes of inquiry; a way of doing research that he viewed as lacking "empirical and explanatory rigour"; and an intellectual bias in the discipline against policy analysis and applied research, which some viewed as less prestigious than theoretical advancement of the field. Inevitably, a geographical perspective is engrained in the policy process[4], he argues. Nonspatial policies have spatial consequences, from local to global scales; Policies also impact different socioeconomic groups, understanding local contexts and geographical differences is essential to avoiding inequalities and social injustices. Most importantly, geographical information can support the development of target policies that take such variations in localities and conditions into consideration.

Building blocks of NbS implementation

Here, I take the discussion from the previous section a step further and describe how we can think about NbS, not just in relation to geography as a discipline, but how research in geography can advance the implementation of NbS. To do so, I developed a simple conceptual diagram that illustrates the shift from recognizing the potential of NbS and its inclusion in high-level targets (**Figure 2**). Examples of targets that NbS can contribute to include the SDGs, Bonn Challenge, NYDF goals, and Global Biodiversity Framework Targets, as well as NDCs and other national and sub-national targets. for meeting that potential. These targets send a signal that NbS should be a policy priority. The next question is then how do we reach those targets – i.e., how do we go about implementing them?

I take inspiration for NbS implementation from broadly applicable principles for policy implementation. Specifically, the translation of high-level targets into a more actionable agenda and subsequent implementation plan are two widely recognized steps what is commonly known as "the policy process" or "policy cycle" (Jann & Wegrich, 2006; Lasswelll, 1956). While the exact stages and descriptions of the policy process may vary, they generally include: problem definition, agenda-setting, policy formulation, policy implementation, and policy evaluation. Problem definition and agenda-setting involve identifying a problem and raising it as a public issue. Policy formulation is when objectives are set, and actions are considered to meet those objectives. Policy implementation takes place once actions have been decided on and responsibilities and resources for taking action have been delegated. Between formulation and implementation, discussions are also often had regarding possible constraints, such as budgets and capabilities. Policy evaluation is when the activity is assessed and measured to determine whether the problem has been solved, or feedback is elicited to improve the activity. It is important to note, however, that this model represents an idealized process and is only meant to serve as a heuristic for policy analysis. In reality, the stages of the policy cycle may overlap and influence each other, as parts of an iterative and ongoing process, rather than following a purely linear structure (Sutton, 1999).

[4] The policy process describes the series of steps taken to reach a specific policy outcome. See the next subsection (**Building blocks of NbS implementation**) for more information.

Another useful heuristic for thinking about how to overcome the NbS potential-to-implementation gap is the "evidence-informed policy and practice pathway" outlined by Bowen & Zwi (2009). The authors, both members of the public health community, identify a need to better contextualize evidence for policy and practice. Their proposed pathway consists of three stages that move evidence between a policy idea and action: sourcing of evidence, use of evidence, and implementation of evidence. They also recognize that contexts differ, and how evidence is implemented may need to be adapted to specific circumstances. In addition, individuals and organizations can play a significant role when deciding to adopt a piece of evidence or not.

I take the aforementioned heuristics, together with literature on NbS, to derive my conceptual diagram. Based on these, I highlight three core building blocks[5] that are essential to advancing policy development and subsequent implementation: (1) knowledge synthesis; (2) planning & decision-making; (3) policy & financing mechanisms (**Figure 2**). These building blocks can enhance and support the various stages of the policy process. First, rigorous knowledge synthesis on aspects of NbS provides a useful source of evidence that can be utilized to identify information and action gaps, best practices, and support targeted policy formulation. Second, good planning and decision-making are important for prioritization of NbS activities and allocation of resources, in particular when undertaken collaboratively with stakeholders who may be integral to policy adoption. Third, well-designed policy and financing mechanisms are critical, as they provide channels for bringing NbS activities into fruition. Furthermore, the building blocks reinforce each other. Access to a comprehensive and diverse set of knowledge, for example, can help decision-makers explore different policy options and make context-appropriate action plans and choices. Research from the discipline of geography can contribute to all three implementation building blocks, for reasons described in the last two subsections.

Additionally, knowledge synthesis, planning and decision-making, and policy and financing mechanisms are linked to enabling factors for NbS and help to address implementation barriers (Albert et al., 2021; Martin et al., 2021; Nolan et al., 2021; Pérez-Cirera et al., 2021; Sarabi et al., 2019; Schulte et al., 2022). A WWF report on conditions to enable nature-based solutions, for example, names inclusive governance, smart spatial planning, and progressive economic and financial regulation, as systemic enablers for implementing effective and scalable NbS (Pérez-Cirera et al., 2021). Similarly, Sarabi et al. (2019) find knowledge sharing, economic instruments and incentives (including fiscal), and plans, program and legislations to be enablers, though the latter can also be barriers. (Albert et al., 2021) also identify five principles of planning NbS, notably basing it on evidence, as well as integration, place-specificity, equity, and transdisciplinarity.

[5] While the components of the conceptual diagram are not exhaustive and many forces beyond those that I depict may be present, the diagram is still useful for visualizing some elements that are fundamental to the implementation of NbS.

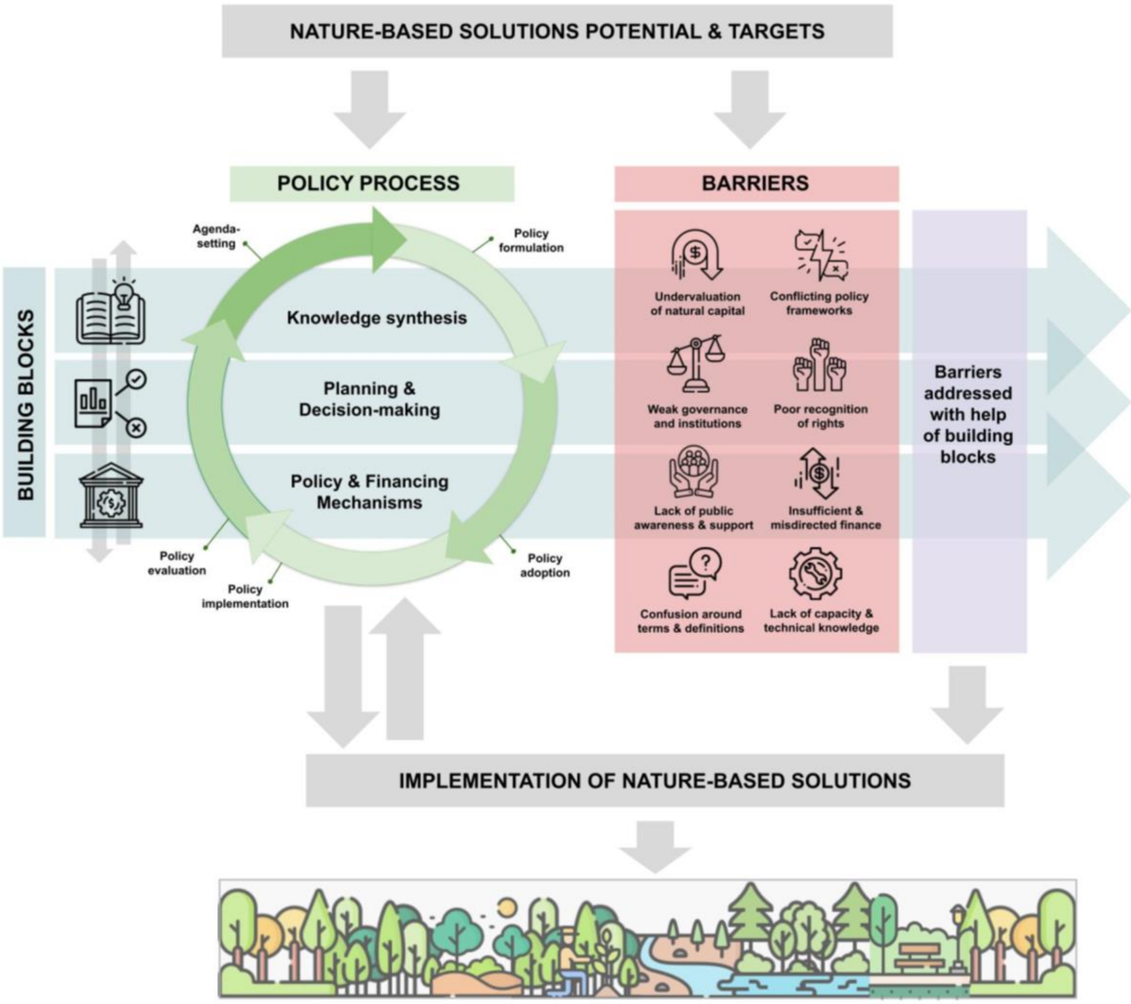

Figure 2. Conceptual diagram of NbS potential to implementation (own illustration; see **Appendix** for icon image credits).

III. METHODOLOGICAL FRAMEWORK

III.1 Reshaping research during a pandemic

In Spring 2019, I wrote a proposal for a PhD project that would involve case studies based on fieldwork conducted in two countries with differing NbS contexts. The proposal was successful. By Spring 2020, the world had shut down due to the spread of the Coronavirus (COVID-19). As we all experienced, there was significant uncertainty about what the next few weeks (even months) would look like, and when newly implemented restrictions would ease. I had not yet started any preparations for fieldwork, so my supervisors and I made an early decision to change the trajectory of my thesis, rather than wait for countries to reopen at an unknown future date.

With the new constraints of the COVID-19 pandemic in place, we were forced to think about what was possible from the physical boundaries of my home. That meant a lot of the research would likely be virtual. Additionally, we had seen what type of data would be possible to elicit. Not being able to go into the field opened door to look more deeply at secondary information, or what was already existing. There is often a pressure to publish work that is new and exciting. It can be difficult to take time to pause and assess what research is currently out there and importantly, what the quality is, how we can learn from it and translate into actionable policy. Yet, secondary research can produce novel outcomes. As such, it has now become a strength and focus of my research, as is elaborated on in the next two sections (**Chapters III.2 and III.3**). Had I not had the opportunity to reflect, I probably would not have realized the value of taking that step back from the topic and turning that into a rigorous research approach. This has allowed me to produce work that draws on previous research to develop new theories and perspectives that contribute to ongoing debates in NbS dialogues.

Furthermore, the virtual experience was well suited to forming collaborations. In the last three years, I built relationships with partners internationally at the International Institute for Applied Systems Analysis in Austria and Conservation International and the Environmental Defense Fund in the United States. Granted, this was possible before the pandemic, but as COVID-19 made the possibility of working online the only option, it really tested the limits of digital exchange. For example, I learned there are many advantages to online working, such as being able to engage people in different countries or institutes, suggesting potential to promote cross-disciplinary work. At the same time, there are challenges, like missing personal connection to colleagues.

Nevertheless, the lessons learned from conducting research in a pandemic could be useful for researchers facing other constraints in non-pandemic times, including those who focus on hard-to-reach areas such as conflict zones or who may have limited resources and be unable to travel.

III.2 The importance of stepping back

Despite the desire and need for evidence-based policy and decision-making to address global challenges such as climate change, the ability of researchers to deliver said evidence in a consistent and timely manner remains limited (Balbi et al., 2022). At the same time, we know more than we have ever before. This saturation of research has advantages and disadvantages. On the one hand, there is a large pool of evidence to draw from to elicit lessons learned and identify potential ways forward (Berrang-Ford et al., 2020). This evidence can be consolidated to improve the performance and robustness of policy interventions. On the other hand, it is impossible to know all the literature on climate change as there is simply too much (Callaghan et al., 2020; Nunez-Mir et al., 2016). Machine-learning methods can be useful complements for identifying and analyzing literature in this era of 'big data'. Nevertheless, thorough assessments by experts are still needed to verify and evaluate the literature (Callaghan et al., 2021).

Furthermore, solving collective problems requires bodies of collective knowledge. These, however, remain rare. An evaluation of the literature on climate adaptation, for example, notes that working in disciplinary silos is at times necessary, but can sometimes lead to oversimplified problem solutions that are not feasible in practice (Sietsma et al., 2021). More effort is needed to bring evidence together and rigorously evaluate it in the context of similar studies. As Chalmers et al. (2002) wrote: "Science is supposed to be cumulative, but scientists only rarely cumulate evidence scientifically." This thesis thus responds to the needs of the field of geography in a new era of research and approaches the research as such: flexibly, transparently, and with interdisciplinarity. These three ideas are taken as methodological principles that guide the research.

Additional methodological principles this thesis adheres to include openness, collaboration, and reflection. This is where the idea of taking a step back is valuable from a research perspective, as zooming out and taking stock of what is being done and has been done can help determine where we need to go. What do we know? And how do we know it? What do we not know? In addition, it allows us as researchers to let go of epistemological and ontological biases and approach our work from a different perspective. As researchers, we often work within an existing research agenda, whether it be to obtain funding that aligns with specific calls or to fit into a current debate to ensure a manuscript relevant for publication. Taking a step back allows us to critically reflect on the framings we are working within. How are these narratives shaped? Based on what assumptions and what evidence? Who is involved in the process of creating that evidence and making choices about how it is communicated and to whom? Why are certain narratives elevated more than others? These questions are not necessarily meant to be answered directly but are ongoing in the background of my research process, as touched on in previous sections of this thesis.

III.3 Research methods & limitations

As discussed in the previous sections, in reshaping my research due to COVD-19, I identified a valuable opportunity to step back and take stock of the current research landscape driving NbS implementation. As such, the work in the four research outputs of this thesis is primarily secondary research and synthesis. Data and information were extracted from secondary sources such as peer-reviewed articles and publicly available documents. They were then analyzed quantitatively, qualitatively, or in both ways depending on the specific research objective. In some outputs, the secondary research is complemented by interviews, theory development, or modelling work.

In the remainder of this section, I provide more background on three core groups of methods and tools that influence this thesis – literature review and synthesis; global computational models; and interview and qualitative inquiry – and reflect on the overarching limitations of my approach. The detailed methods I apply for each component of this thesis are defined in the individual sub-chapters of the **Research Outputs** section (see **Chapters IV.1, IV.2,** and **IV.3**).

Literature review & synthesis

There are many advantages to using a methodology founded on secondary research and synthesis. Existing information can provide important context for developing a research problem and framework for evaluating new information (Stewart & Kamins, 1993). Furthermore, large amounts of information are readily available, which can save researchers time and resources (Rabinovich & Cheon, 2011). There is also a certain level of integrity associated with this approach, as the information analyzed in secondary research is produced separately (and prior) to the objective of the research, restricting some potential bias in the evidence creation process.

The specific synthesis method applied largely depends on the research objective. In the medical community, where this type of secondary synthesis research has been ongoing for decades, a number of methodological papers provide an overview of approaches and guidelines for undertaking evidence synthesis and review work. Kastner et al. (2012), for example, identify at least 25 methods for synthesizing information from literature. Grant & Booth (2009) analyze 14 different review types and associated methodologies. Ultimately, the choice of review method applied in any given study depends on the exact research question and objectives. In this thesis, I apply systematic map and review (**Chapter IV.1**), critical review (**Chapter IV.2**), and narrative review methods (**Chapters IV.3**).

Systematic reviews use structured (i.e., systematic) and explicit methods for all stages of the review, including literature selection, critical appraisal, data collection, and analysis (Kastner et al., 2012).

They are valuable for providing the researcher with a comprehensive overview of the literature, for example, identifying areas of strong evidence on a specific topic, as well as gaps and needs for future research. Critical reviews focus on highlighting and evaluating the significant literature on a topic (Grant & Booth, 2009). They are characterized by extensive research, which often results in conceptual or theoretical contributions, but lack formal quality assessments. Narrative reviews, or summaries, also tend to be less structured and more interpretive than other types of reviews, which is particularly useful when dealing with multiple types of evidence (Dixon-Woods et al., 2005). This allows the researcher to easily bring together and describe primary evidence, while providing commentary or building theoretical ideas.

Global computational models

I am influenced by global modelling frameworks in this thesis, as they provide the motivation and setting for my research (**Chapter IV.2**). In particular, I consider global land-use models, especially those coupled into integrated assessment models. Integrated assessment models are complex computational models that represent interconnected systems, in particular human and natural Earth systems (Edmonds et al., 2012). Components of IAMs may include the economy, energy, land use, ecosystems, the carbon cycle, and atmospheric chemistry.

The Global Biosphere Management Model (GLOBIOM) is an example of a global economic land use model. Examples of integrated assessment models include the Global Change Assessment Model (GCAM), IMAGE (Integrated Model to Assess the Global Environment), and MESSAGE (Model of Energy Supply Systems And their General Environmental Impact). While IAMs are useful for generating scenarios that illustrate potential futures, they are also limited in their application to produce feasible, realistic solutions (Riahi et al., 2015). This is in part due to their lack of representation of social dynamics. Producing those types of solutions is not necessarily the job of IAMs, but is often misunderstood to be (Jewell, 2019). In addition, IAMs have become very powerful and influential at the science-policy interface, making closing the gap between potential futures and feasible solutions even more important (Beck & Mahony, 2018; van Beek et al., 2020). As such, in **Chapter IV.2**, we explore how to overcome this gap.

Interviews & qualitative inquiry

In this thesis, I draw from interviews and qualitative inquiry in two ways. In one sub-chapter of this thesis, I specifically use semi-structured interviews to elicit additional information from experts to complement the results of a critical literature review (**Chapter IV.2**). There are different definitions of qualitative interviews and the purposes they serve (DeJonckheere & Vaughn, 2019). These range from contributing knowledge on a topic to understanding the experiences for the interview participants. In semi-structured interviews, the researcher uses a set of pre-determined questions or topics as a guide, though the responses from participants are still open-ended and can go in different directions (Jamshed, 2014). For me, incorporating interviews into my methodology had the advantage of bringing to light information that I would not have come across otherwise, in many cases because the experiences the participants talked about in the interviews were not published in the literature. In addition, the interviews served as a validation for the review, as they allowed me to collect information from different perspectives – those of the interview participants – and triangulate these with the literature and my own interpretation of the literature. Further information on the interviews, such as selection of participants, duration of the interviews, and how they were coded and analyzed is provided in **Chapter IV.2.**

The rationale behind the interviews is also closely tied to the qualitative inquiry approach that underlies this thesis. Qualitative inquiry typically takes an inductive approach, meaning researchers start with broad research questions, approaches, and objectives that become refined as information on the topic is collected (Liamputtong, 2019). Or, as Strauss & Corbin (1998) describe inductive analysis: "The researcher begins with an area of study and allows the theory to emerge from the data" Core elements of qualitative inquiry include observation, openness, and depth (Patton, 2002) While qualitative inquiry is usually applied to participant-oriented research, I apply these elements as principles that guide my research, as mentioned in **Chapter III.2**). In my case, my data sources are not just people, but different forms of qualitative information, including evidence from the literature, that help me understand the context and topics I am exploring in my work.

Research limitations

Of course, there are also some limitations to a secondary research and synthesis approach. For one, my research is based on the best available data. Information is not always available for all study areas, sectors, or topics. Some countries, for example, are not as well researched as others for reasons as wide-ranging as lack of funding to lack of access. While a contribution of my research is being able to identify where these gaps are, this can also make drawing broad insights challenging. In these cases, there may be lessons learned from similar contexts where we do have information that can potentially be applied or used as a starting point for research in those areas where data is lacking.

Another limitation is that there is often a time lag in the publication of data and journal articles. While this allows for lessons to still be learned from the past, it may exclude recent developments from being included in research results. This was one reason that we supplemented the research in **Chapter IV.2**, where the topic is particularly dynamic, with interviews. Finally, secondary data sources are very heterogeneous. A range of methods are used, and it can be difficult to assess the quality of the research. Despite secondary research being based on data or reported results from other studies, the researcher does have influence over how that information is synthesized and, in some cases, aggregated. This is where bias may potentially occur, as some subjectivity is inevitable. As such, it is important for researchers to reflect on their positionality to understand how their experiences may shape the work they are undertaking.

Positionality refers to "notion that personal values, views, and location in time and space influence how one understands the world" and "consequently, [that] knowledge is the product of a specific position that reflects particular places and spaces" (Warf, 2010). The position of the researcher may influence every step of the work, from developing the research question to the choice of methods to the interpretation and communication of the results. This view is a shift from traditional notions of objectivity in research and the positivist idea that research is an independent process that can be separated from the researcher – what Donna Haraway (1988) calls "the god-trick of seeing everything from nowhere." Haraway instead makes the case for acknowledging that knowledge stems from specific contexts and positions in space and time, a concept she terms "situated knowledges". While we will never be able fully situate our knowledge, acknowledging positionality is a valuable exercise in understanding the perspectives and limitations influencing research processes (Rose, 1997).

I certainly have past experiences that shape my positionality and may have an impact on the knowledge created through my research. For example, before starting my PhD I worked for a small climate advisory firm on projects at the science-policy interface. My time there motivated a lot of the questions I was interested in exploring in my doctoral research. In one project, I tracked progress towards commitments to end deforestation, halt unsustainable forest activities, and promote finance and improved governance for forests. Seeing the slow progress year after year piqued my interest in the drivers of implementation of such activities, and nature-based solutions more broadly. Furthermore, having engaged closely with diverse stakeholders, I was interested in producing research that was action-oriented and could meet the needs of different audiences. In addition, I often come at my research from a normative stance, thinking of the broader implications of the research, from the design stage through interpretation. As such, that job has influenced the research questions I have asked, and how I discuss the results in my papers.

IV. RESEARCH OUTPUTS

IV.1 What influences the implementation of natural climate solutions? A systematic map and review of the evidence

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Abstract

Emerging research points to large greenhouse gas mitigation opportunities for activities that are focused on the preservation and maintenance of ecosystems, also known as natural climate solutions (NCS). Despite large quantifications of the potential biophysical and carbon benefits of these activities, these estimates hold large uncertainties and few capture the socio-economic bounds. Furthermore, the uptake of NCS remains slow and information on the enabling factors needed for successful implementation, co-benefits, and trade-offs of these activities remain underrepresented at scale. As such, we present a systematic review that synthesizes and maps the bottom-up evidence on the contextual factors that influence the implementation of NCS in the peer-reviewed literature. Drawing from a large global collection of (primarily case study-based, *N* = 211) research, this study (1) clarifies the definition of NCS, including in the context of nature-based solutions and other ecosystem-based approaches to addressing climate change; (2) provides an overview of the current state of literature, including research trends, opportunities, gaps, and biases; and (3) critically reflects on factors that may affect implementation in different geographies. We find that the content of the reviewed studies overwhelmingly focuses on tropical regions and activities in forest landscapes. We observe that implementation of NCS rely, not on one factor, but a suite of interlinked enabling factors. Specifically, engagement of indigenous peoples and local communities, performance-based finance, and technical assistance are important drivers of NCS implementation. While the broad categories of factors mentioned in the literature are similar across regions, the combination of factors and how and for whom they are taken up remains heterogeneous globally, and even within countries. Thus, our results highlight the need to better understand what trends may be generalizable to inform best practices in policy discussions and where more nuance may be needed for interpreting research findings and applying them outside of their study contexts.

Keywords

natural climate solutions; nature-based solutions; climate change policy; land-based mitigation; systematic review; systematic mapping; global environmental assessment

1. Introduction

It is estimated that natural climate solutions (NCS) – carbon sequestration activities that focus on the "protection, restoration and sustainable management of terrestrial and coastal ecosystems and landscapes" – have the potential to provide a third of emission reductions needed to keep global temperature rise below 2 degrees Celsius (Griscom et al., 2017). However, an understanding of how, if, and where these potentials can be met and with what trade-offs and co-benefits remains underresearched (IPCC, 2019). As such, attention is shifting to the need for more information and data on the feasibility of NCS activities, in particular at the country-level and lower (Brancalion et al., 2019; Chazdon et al., 2020; Lamb et al., 2021; Roe et al., 2021).

In addition, the dynamics of implementation at scale remain unclear. Local stakeholders – including communities, companies, and governments – have an important role to play in protecting and restoring forests and natural ecosystems (Mansourian, 2016; Ostrom, 2009; Seymour, 2020). For example, is there buy-in from these actors for these activities? What does the political economy look like? Even with stakeholder support – what kind of information and finance is needed, and is it accessible? Many questions regarding NCS are analogous to concerns that have been faced in Reducing Emissions from Deforestation and forest Degradation (REDD+) efforts. Evidence from experiences implementing REDD+ provide a useful bridge for discussions regarding NCS. For example, research indicates that there has been some progress in advancing REDD+ objectives, but transformational change remains limited because necessary factors to operationalize REDD+, such as strong leadership and finance, remain weak (Korhonen-Kurki et al., 2019). Communities are intended implementers and beneficiaries of REDD+, but this has not been reflected on the ground (Duchelle et al., 2018; Skutsch & Turnhout, 2018). Additionally, designing REDD+ with incentive-based conservation challenges and other environmental goals in mind has led to mixed results due to conflicts with political and societal priorities and, as such, low political and social feasibility (Rosa da Conceição et al., 2018).

Furthermore, there has been a growing trend towards harnessing nature to implement the Sustainable Development Goals, including as a climate solution, while recognizing nature alone is not enough (Anderson et al., 2019; Smith et al., 2019). There is a clear need to understand the evidence base that exists around implementation, to more effectively communicate this information to decision makers and stakeholders, and to identify and address key knowledge gaps (Malhi et al., 2020; Walsh et al., 2021). In addition, it is important to understand how nature can realistically contribute to climate targets, including what types of activities lead to what outcomes (e.g., avoided emissions vs. removals). This is increasingly important given the urgency of climate change mitigation and as more attention is given to NCS in debates around voluntary carbon markets, emissions trading systems, and climate ambition.

This study contributes to the global assessments and evidence on the role of nature for climate change mitigation. Although individual studies and reviews have investigated implementation of NCS activities on local levels (Hoang et al., 2019; Huang et al., 2019; Uisso et al., 2019), this synthesis is a first attempt to provide a broad assessment of implementation that can inform further research and policy directions. This is particularly valuable for informing meso-scale planning and designing non-quantitative indicators for monitoring NCS, such as when setting national targets and extrapolating insights from specific case studies may present biases due to heterogeneity within the country. Furthermore, this study contributes to an emerging research field to advance the implementation of NCS by complementing recent publications on the potentials, costs, and feasibility of NCS (Griscom et al., 2020; Roe et al., 2021). Finally, it develops a comprehensive and in-depth database that can facilitate a move towards more normative research (Nielsen et al., 2019), for example, by highlighting key research questions and validating or challenging widely held assumptions and narratives around the potential of NCS, the current discourse and state of research, and the realities on-the-ground.

Specifically, we (1) clarify the definition of natural climate solutions, including in the context of nature-based solutions (NbS) and other ecosystem-based approaches to addressing climate change; (2) present a systematic mapping and review of the literature on NCS implementation; and (3) reflect on characteristics of NCS that are relevant to designing and implementing socially just solutions and achieving long-term positive change.

2. Defining natural climate solutions

Researchers frequently encounter new terms and ideas. These are often integrated in policy, including high-level agreements and conventions. Translating these into action and ensuring they are implementable requires a common understanding of what these terms mean in science, policy, and practice (Abson et al., 2014; Brand & Jax, 2007; Star & Griesemer, 1989).

"Natural climate solutions" is a subset of the umbrella concept of "nature-based solutions". NbS are defined by the International Union for Conservation of Nature as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016). A second definition of NbS from the European Commission describes them as "solutions inspired and supported by nature, designed to address societal challenges which are cost-effective, simultaneously provide environmental, social and economic benefits, and help build resilience" (EU Commission, 2021; Raymond et al., 2017). NbS also include other "nature-based" approaches such as ecosystem-based adaptation (EbA) and mitigation, green infrastructure, and eco-disaster risk reduction (Seddon et al., 2020). These are just a few examples. Definitions of NbS are often adjusted depending on the context, initially raising concerns around the vagueness of the term NbS (Bennett et al., 2009; Nature, 2017; Nesshöver et al., 2017; Ring et al., 2010).

The concerns around the term NbS are valid and similarly applicable to NCS. Natural climate solutions is a relatively new term in environmental research and is quickly being adopted in the policy world (**Table 1.1**). It was first defined in a 2017 study, referring to the "conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands" (Griscom et al., 2017). According to a follow up study, a key difference between NCS and NbS is that NCS focuses on climate change mitigation while NbS also includes adaptation and non-climate objectives (Griscom et al., 2020). In that regard, NCS can be understood as largely overlapping with the term "land-based mitigation", as referred to in the IPCC (IPCC, 2019). It is important to clarify these distinctions, as without clear definitions, parameters, and methodologies, NCS risks losing clout (Brandt et al., 2013; Davis, 2008; Hanson et al., 2020; Lamb & Schmidt, 2021). Furthermore, having a well-established NCS concept is essential to driving and evaluating the implementation of NCS activities.

Table 1.1. Examples of references to natural climate solutions in policy and academia

	Author	Source	Definition or reference
Policy briefs	The Nature Conservancy	Website	"Natural climate solutions are conservation, restoration and improved land management actions that increase carbon storage or avoid greenhouse gas emissions in landscapes and wetlands across the globe."
	Conservation International	Website	"Any action that conserves, restores or improves the use or management of these ecosystems — *while*, and this is important, increasing carbon storage and/or avoiding greenhouse gas emissions — can be considered a "natural" climate solution."
	Nature4Climate	Website	"Approaches used to limit global warming by working with natural and managed forests, grasslands and agriculture, as well as wetlands systems to lower concentrations of greenhouse gasses in the atmosphere. This is accomplished by employing land use and management strategies that avoid greenhouse gas emissions and enhance carbon sequestration."
	World Economic Forum	Website	"The Natural Climate Solutions (NCS) Alliance aims to scale up affordable natural climate mitigation solutions for achieving the goals of the Paris Agreement on climate change. These include; reforestation protection and conservation, livestock, animal and land management, and coastal wetland and peatland restoration, among a wide array of cost-effective solutions."
	World Business Council for Sustainable Development	Proposal	"Nature-based Solutions can remove up to one-third of the necessary CO2 reductions. The Natural Climate Solutions initiative led by WBCSD seeks to make this possible by enabling private sector investment into these solutions."
Academic literature	Griscom et al., 2017	Article, *PNAS*	"Protection, restoration and sustainable management of terrestrial and coastal ecosystems and landscapes such as forests, grasslands, agricultural lands and wetlands" via "conservation, restoration, and

		improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands."
Anderson et al., 2019	Policy Forum, *Science*	"Although analyses of NCS have some differences in the GHG fluxes they consider, all include emissions sources (such as deforestation, land-use change, and agricultural practices), emissions sinks (such as reforestation and restoring degraded lands), and non–carbon dioxide (CO2) agricultural emissions (such as methane from livestock)."
Fargione et al., 2018	Article, *Science Advances*	"Natural climate solutions (NCS), a portfolio of discrete land stewardship options, are the most mature approaches available for carbon conservation and uptake compared to nascent carbon capture technologies and could complement increases in zero-carbon energy production and energy efficiency to achieve needed climate change mitigation […] We consider 21 distinct NCS to provide a consistent and comprehensive exploration of the mitigation potential of conservation, restoration, and improved management in forests, grasslands, agricultural lands, and wetlands."
Griscom et al., 2019	Letter to the editor, *Global Change Biology*	"Land-based options include natural climate solutions (NCS) which use ecosystems for removal and storage, and off-site storage using options like bioenergy with carbon capture and storage (BECCS)."
Hohlwegler, 2019	Article, *Advances in Geosciences*	"Mitigation efforts in line with efficient land management actions concerning, e.g., peats and soils, designated as "natural climate solutions" […]"
Griscom et al., 2020	Article, *Philosophical Transactions Royal Society B*	"NCS can also be referred to as Nature-based Solutions (NbS), although this is a broader term which also refers to climate adaptation, food security, water security, human health, and social and economic development."
Baldocchi, 2020	Article, *Global Change Biology*	"We are at the verge of capturing ecosystem scale trends in the breathing of a changing biosphere. Consequently, flux measurements need to continue to report on future conditions and responses and assess the efficacy of natural climate solutions."

To date, the academic research that uses the term natural climate solutions is limited but rapidly growing, increasing nearly eight-fold between November 2019 and September 2021 (see section **3.1**). The general consensus from experts in the academic literature maintains the distinction that NCS focus on climate change mitigation activities (Griscom et al., 2020; Hohlwegler, 2019). As such, we adopt this definition of NCS for our study. However, we also recognize the important relationship between NCS and NbS in understanding biodiversity, livelihood, and adaptation impacts. These are captured as co-benefits in our study.

3. Methods

This study systematically maps the global evidence base on NCS implementation, with a focus on the enabling factors, in the scientific literature by reviewing ex-post studies. Here, we describe our approach to clarifying the definition of NCS; identifying, selecting, and reviewing the literature; and subsequently analyzing the data.

3.1 Scoping of terms

To prepare for this systematic review, we first conducted a quick scoping exercise to understand how the term "natural climate solutions" appears in the academic literature. This was essential to developing a common understanding of the terminology among the author team and providing a clear framing for the review. We searched for the term "natural climate solutions" on Scopus in November 2019 and found just eight peer-reviewed documents, two of which were led by the same author. Because much confusion surrounds the terms NCS and NbS, we also conducted a search for the term "nature-based solutions", scanning primarily for literature that contained definitions of the term. The results include literature dating back to the emergence of term and caveats around it as well as more recent studies outlining current understandings of NbS. Finally, we also searched for definitions of NCS on Google and relevant initiative websites we were aware of to observe how the terminology is used outside of the academic literature.

We conducted the same search of the term "natural climate solutions" on Scopus in September 2021, at the time of submission of this review paper, and found 62 results. The reason for this was to gain insight on how the research landscape on the topic had changed over the course of the review period.

3.2 Review criteria, search, and screening

Using twenty natural climate solutions pathways derived from the IPCC as a starting point (Griscom et al., 2017), we iteratively developed a search query to identify the body of literature for our review (see **Appendix**). These pathways build on the land-based – or Agriculture, Forestry, and Other Land Use (AFOLU) – climate solutions previously assessed by the United Nations' Intergovernmental Panel for Climate Change (IPCC, 2019). In addition, they include activities in wetlands and other natural ecosystems not captured by AFLOU. Our search query thus encompasses the literature on forests, agricultural lands, grasslands (including savannahs), and wetlands (including peatlands) that also include reference to key terms and synonyms related to climate change mitigation and implementation. We limit our search to documents uploaded onto the Web of Science and Scopus platforms by November 1, 2019 or prior. As such, our search is limited to peer-reviewed literature and excludes grey literature.

Our search query provided us with 2,939 initial results on Web of Science and Scopus. To limit the scope of our study to subject-relevant papers and evidence on activities that have already been implemented, we developed a set of inclusion/exclusion criteria to screen the abstracts of the initial search results (see **Appendix**). The main criteria for inclusion were that studies focus on at least one activity that qualifies as an NCS and that they contain information on the implementation context, such as barriers and enablers. Studies on adaptation and technical aspects of implementation were excluded, as were systematic reviews and meta-analyses to avoid double counting. Similarly, studies that were simulations or models of possible activities and potentials were mostly excluded, with a few exceptions when a study still provided useful and relevant information on the implementation context.

Furthermore, we focus on studies in the English language that reference at least one enabling factor. These factors are broadly categorized into social, economic, political, institutional, financial, technical, and biophysical factors, building off the enabling conditions and barriers to AFLOU mitigation measures presented in the 5th IPCC Assessment Report (IPCC, 2014). After screening the titles and abstracts of our initial 2,939 search results using our inclusion/exclusion criteria, we narrowed our results to 345 papers. However, in the process of the full-text review, a further 134 papers were excluded, resulting in a final database of 211 studies (7% of the initial results) that met our review criteria. This demonstrates the thoroughness and selectivity of our search criteria to ensure our database captured experience-based evidence, rather than hypothetical or speculative. In addition, it indicates that while a large number of papers provide information on NCS activities, a relatively small number of papers provide detailed insights on specific contextual enabling factors and conditions around implementation.

3.3 Data extraction, coding, and analysis

Our review consisted of collecting two primary types of information: data for mapping the overall evidence base around NCS implementation and data for the analysis of the enabling factors related to implementation. To capture the descriptive data for the mapping, we extracted the metadata on each document (i.e., author, title, key words, journal year) as well as the study methods, geographical location(s), NCS activities and land types, any relevant programs (e.g., REDD+ or Clean Development Mechanism), and implementing institution(s), as applicable. For the data on the enabling factors, we developed a codebook detailing possible factors that was grouped into the same categories we considered in our literature screening (institutional, social, environmental, economic, technological, and financial), as well as possible co-benefits (see **Appendix**). The database also allowed for the coder to provide comments on specific factors for each document, or general comments, to ensure that qualitative information or examples could be recorded as necessary. Note that we clustered together factors into simplified groups for the analysis. When we clustered, we just marked if any of the factors were mentioned to avoid double counting, however, we retained the original data for sub-sample analysis.

To test our codebook and approach, three coders initially coded sub-samples. The results of the test were discussed among the coders to ensure a common understanding of the codebook. Next, the codebook was applied to all the documents and data was extracted from the remaining documents by two coders. For documents where a coder was uncertain, they made a note and the results were discussed as a team.

We cleaned and analyzed the coded data using R. We conducted analysis on the dataset as a whole, mapping out the overarching trends, geographical insights, and information on specific NCS activities. We then evaluated the enabling factors and co-benefits mentioned in the literature, providing examples for context where possible. We also categorized the NCS activities into protection, restoration, and management activities for some analyses, expanding on groupings from Griscom et al. (2020) (**Figure 1.1**).

4. Results and synthesis

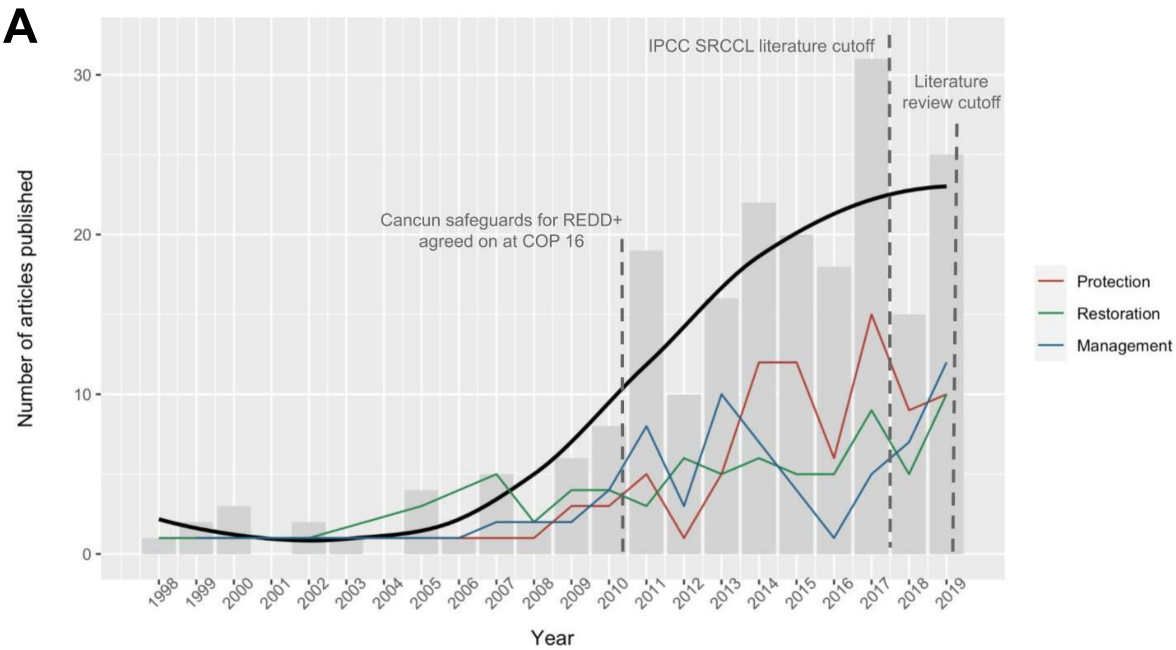
Here we present the main findings and analysis of the reviewed literature. We synthesize these into two sections – an assessment of the overall literature on NCS activities and results on enabling factors for implementation. In the former, we outline historic trends, geographical coverage, and representation of different NCS activities in the literature. In the latter, we highlight important enabling factors and potential variations between geographies. We focus on providing information we have elicited from the dataset and key observations. These are expanded with further insights in the discussion (see section **5.1**).

4.1 Current state of the implementation literature

The majority (83%, n=176) of the 211 studies in our final database were published after 2010 (**Figure 1.1**). Eight studies were published in 2010 and since then the number has steadily increased each year. The historical development of REDD+ may somewhat explain this trend. REDD+ was formalized in 2007 and a number of new funding opportunities emerged in 2009. 43% (n=91) of all the studies we reviewed were associated with REDD+, all but one of which were published in post-2010.

We observed small spikes in the number of studies published in 2011 and 2017. The former can again likely be due to the evolution of REDD+. A possible reason for the higher number in 2017 may be that the literature cut-off date for the IPCC Special Report on Climate Change and Land (SRCCL) was at the end of that year. Furthermore, until 2013 the number of articles published covering protection and management activities followed similar trajectories, likely because these activities were being discussed in articles on REDD+.

Our results also indicate a slow upward trend in the literature on restoration activities. This topic has recently begun to receive more attention in research and policy with the United Nations" Decade of Restoration that began after our literature cut-off date, so we anticipate this will continue. Literature on management activities experienced a lull and now is also increasing. This may also be linked to the interest in restoration. We categorize activities such as planting trees in croplands (including agroforestry) management practices, but by some definitions they may fall under restoration.



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	Protection	Restoration	Management
Forest	Avoided forest conversion	Natural regeneration Reforestation Afforestation	Improved forest management Avoided woodfuel
Agricultural land	---	Biochar	Trees in cropland Nutrient management Optimal grazing intensity Conservation agriculture Improved rice production
Grassland	Avoided grassland conversion	---	Improved fire management
Wetland	Avoided peat impacts Avoided coastal impacts	Peat restoration Coastal restoration River restoration Wetland restoration	---

Figure 1.1. Trends in literature on NCS. (A) Growth in number of articles on NCS published per year through November 2019, including number of mentions of activities falling into different categories (protection, restoration, or management) each year (N=211). Some articles mention multiple categories of NCS (see **Appendix** for analysis of articles mentioning just one category); (B) NCS activities broken down by category of NCS and land type (see **Appendix** for icon image credits).

4.1.1 Geographical coverage

The content of the reviewed studies overwhelmingly focused on tropical regions, specifically Latin America and the Caribbean (LATAM) (25%, n=53), Sub-Saharan Africa (SSA) (20%, n=43), Southeast Asia (SEA) (14%, n=30), and South Asia (SA) (12%, n=25) (**Figure 1.2**). Sixteen studies looked at North America (NA), 12 studies conducted research on East Asia (EA), five on Oceania (OC), and two on the Middle East and North African (MENA) region. Nineteen studies (9%) covered multiple regions. This distribution of geographies in the literature generally aligns with the NCS mitigation opportunities. 61% of the global NCS potential is in tropical countries (Griscom et al., 2020), while there are few feasible NCS opportunities in the MENA region, which is primarily a desert landscape.

Countries with the most coverage in the studies in our database were Indonesia (n=27), Brazil (n=21), Nepal (n=20), Mexico (n=17), Tanzania (n=16), USA (n=16), China (n=14), India (n=14), Cameroon (n=10), and Vietnam (n=10), captured in ten or more articles each. According to Griscom et al. (2020), the top ten tropical countries with the highest technical mitigation potential are Indonesia, Brazil, the Democratic Republic of Congo (DRC), India, Malaysia, Mexico, Colombia, Sudan, Bolivia, and Myanmar**.** Half of these countries (DRC, Malaysia, Colombia, Sudan, and Myanmar) are strongly underrepresented in our database relative to their potential with two or less studies on each.

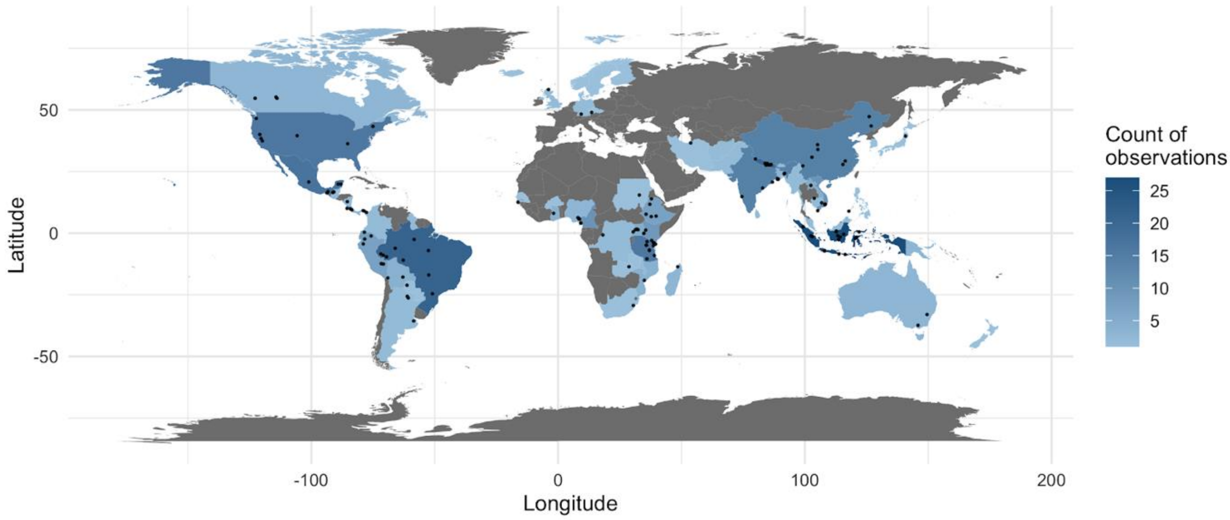


Figure 1.2. Geographical distribution of literature on NCS. Number of papers by country is depictured in blue (N=240 observations in 211 studies). Black dots estimate specific study locations where sub-national information was available on the regional-level or lower (n=141). Multiple locations were given and plotted for some observations.

Our database contained a low count of literature on West Africa. We found nine observations on the sub-region in eight studies (14% of the Africa-focused literature) and covering just four countries, compared to 39 (70%), 11 (20%), and 6 (11%) studies mentioning East, Central, and Southern African countries, respectively. One possibility for this is that the NbS-relevant research in West Africa is primarily adaptation-focused (Chausson et al., 2020).

We also found few studies (3%, n=6) on NCS with a Europe (EUR) focus. Four of these focused on a particular country. The other two studies evaluated the implementation of specific European Union-level policies. This does not necessarily mean that NbS activities are not taking place in the region, but those that are being pursued in the region may fall outside the scope of our study, as we limit our analysis to land-based mitigation measures. This is supported by research by Hanson et al. (2020), which indicates that NbS in Europe may be taking the form of other activities such as green infrastructure development and ecosystem-based adaptation.

4.1.2 NCS activities

Our review assessed studies that implemented NCS activities on four types of landscapes: forests, agricultural lands, grasslands (including savannahs), and wetlands (including peatlands) (**Figure 1.3**). Of 240 observations in 211 studies, activities in forests were a focus of the majority (85%, n=204 observations). A fifth (20%, n=48) of observations provided information on activities in agricultural lands. Few observations in the database are concerned with grassland (3%, n=8) and wetland (10%, n=30) activities, despite substantial theoretical mitigation potential (Griscom et al., 2020). 18% (n=42) of observations, including some of the aforementioned, discussed activities related to more than one land type.

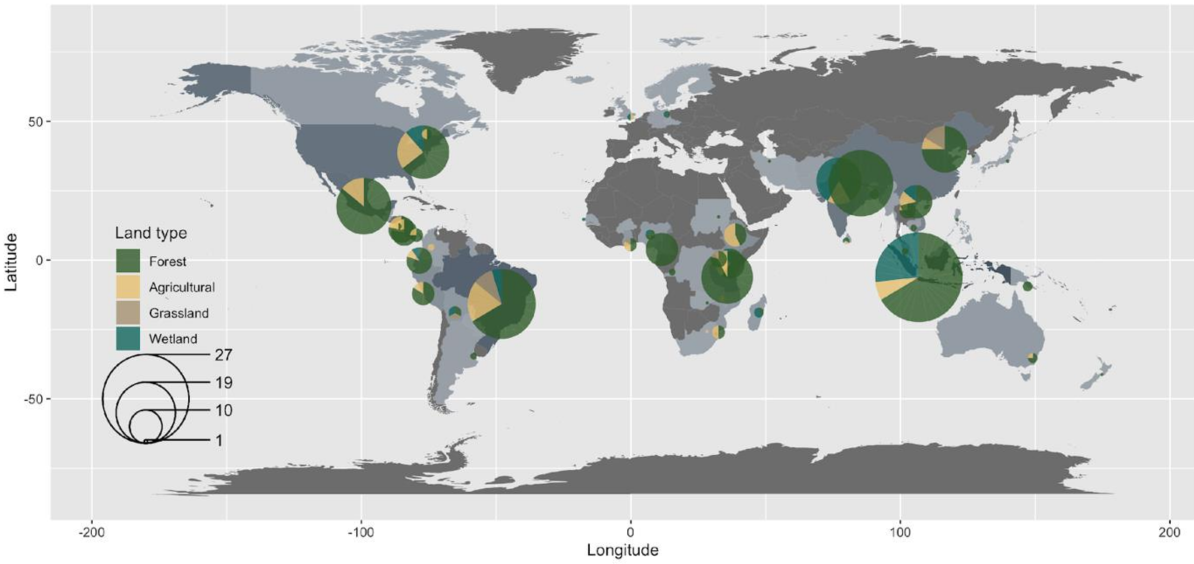


Figure 1.3 Mentions of NCS activities in the literature by country and land type (N=240 observations in 211 studies).

Regions that had the most observations on land types besides forests were LATAM and SSA with agricultural lands (n=16 and n=13, respectively) and grasslands (n=3 and n=2, respectively). Observations with NCS activities in wetlands were observed most frequently in SEA and SA (n=9 and n=6, respectively).

The majority of observations (63%, n=150) mentioned NCS activities in the management category. This was followed by restoration (n=135) and protection (n=117). As mentioned previously, however, many articles touched on NCS activities across multiple categories. Just 6% (n=15) of observations focused solely on protection activities, 7% (n=16) on restoration, and 12% (n=28) on management activities alone.

We provide more detailed results on specific NCS activities and geographic distribution – organized by land type – in the remainder of the section (**Figure 1.4**).

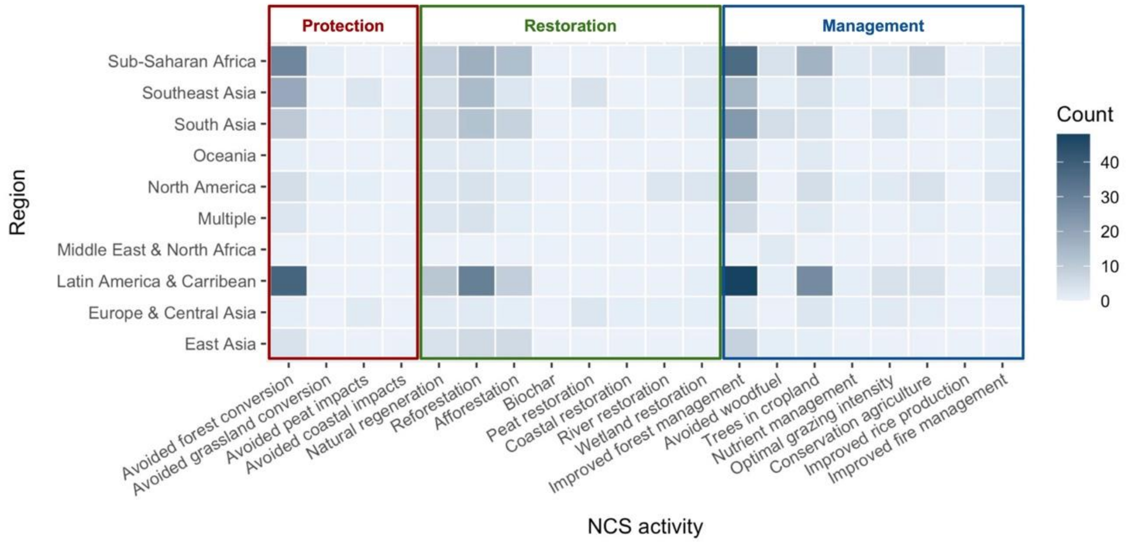


Figure 1.4. Mentions of NCS activities in the literature by region and category (N=240 observations in 211 studies).

Forest. Avoided forest conversion and improved forest management activities, which include natural, plantation, and community forest management practices were identified in nearly half of all observations (46%, n=110 and 51%, n=122, respectively) and received more mentions than any other activity in the reviewed literature. These were closely followed by forest restoration activities – broken down into reforestation, natural regeneration, and afforestation, which we identified separately (in 38%, 18%, and 19% of observations, respectively). Avoided wood fuel was identified in 6% (n=14) observations and fire management in 5% (n=13), though there is some overlap in that activity with grasslands. Forest activities were often mentioned together, in particular in the REDD+ literature. 61% of forest activity observations (n=125) were identified with more than one activity. A REDD+ project or program was associated with 37% of the observations mentioning forest activities in our database (n=75 of 204). This again points to the strong influence of the REDD+ framework in both the design of activities and research.

The literature encompassing forest activities was distributed across global regions. Outside the tropics, the most mentions of forest activities were in observations on the United States (n=12) and China (n=10). Literature on forest activities in the United States focused on both public policies (Cheng et al., 2016) and incentivizing private landowners (Langpap & Kim, 2015; Tian et al., 2015), while the literature on China skewed towards large-scale government-led afforestation projects under national initiatives such as the Grain to Green Program (i.e. Return Farmland to Forest Program) and National Forest Conservation Program (Gong & Zeng, 2019; Liu et al., 2008; Zinda et al., 2017).

Agricultural land. The addition of trees to cropland (i.e., agroforestry, silvopasture) was identified in 23% (n=54) of the observations in our dataset. Conservation agriculture was identified in 8% (n=20) and optimized grazing practices in 6% (n=14). Nutrient management was identified in six observations and improved rice production in just one. Strikingly, none (0%, n=0) of the reviewed studies mention biochar. This may be related to the fact that most of the literature on biochar focuses on technical aspects of implementation, such as the application and effects, and thus would have been excluded in our literature screening.

Observations of NCS activities related to agriculture were concentrated on the LATAM (n=29) and SSA (n=16) regions, in particular Brazil (n=7), Costa Rica (n=5), Mexico (n=5), and Indonesia (n=5). These regions are the largest producers of some of the "big four" commodities (beef, soybeans, palm oil, and wood products) driving ecosystem conversion (Henders et al., 2015). Agricultural natural climate solutions activities were also mentioned in five observations on the United States and four on Tanzania.

Grassland. We considered two activities, fire management and avoided grassland conversion, as possible NCS activities related to grasslands, which we understood to include savannahs. The results on fire management were already reported in the forest section, however, as the activity cuts across both land types and the studies we reviewed only mentioned on wildfires as a source of forest degradation. None of the studies in our dataset looked at fire management in the context of grasslands. Avoided grassland conversion was identified in less than 1% of observations (n=2). Neither study mentioning avoided grassland conversion provides in-depth information on implementation. One study is an article from a decade ago on the role of the United States agriculture sector in climate change (Johnson, 2010). The article touches on the value of grasslands as one ecosystem that can hold carbon in the soil and aboveground biomass when undisturbed. The other is on REDD+ in Ghana and describes the expansion of the program to a savannah area (Asiyanbi et al., 2017).

Other literature mentioning grasslands and savannahs such as the Chaco and Cerrado in Latin America focus on forest and agriculture-related NCS activities (Alves-Pinto et al., 2015; Milmanda Fernández & Garay, 2019; Nolte et al., 2017). This may be because these areas are active agriculture frontiers in the region located amid forests. Furthermore, savannahs are often described as tropical dry forests. While East Asia (i.e., China and Mongolia) is home to large grasslands as well, most of the literature on grasslands in that area did not meet our review inclusion criteria because they were scenarios or model projections and did not contain relevant information on the implementation context.

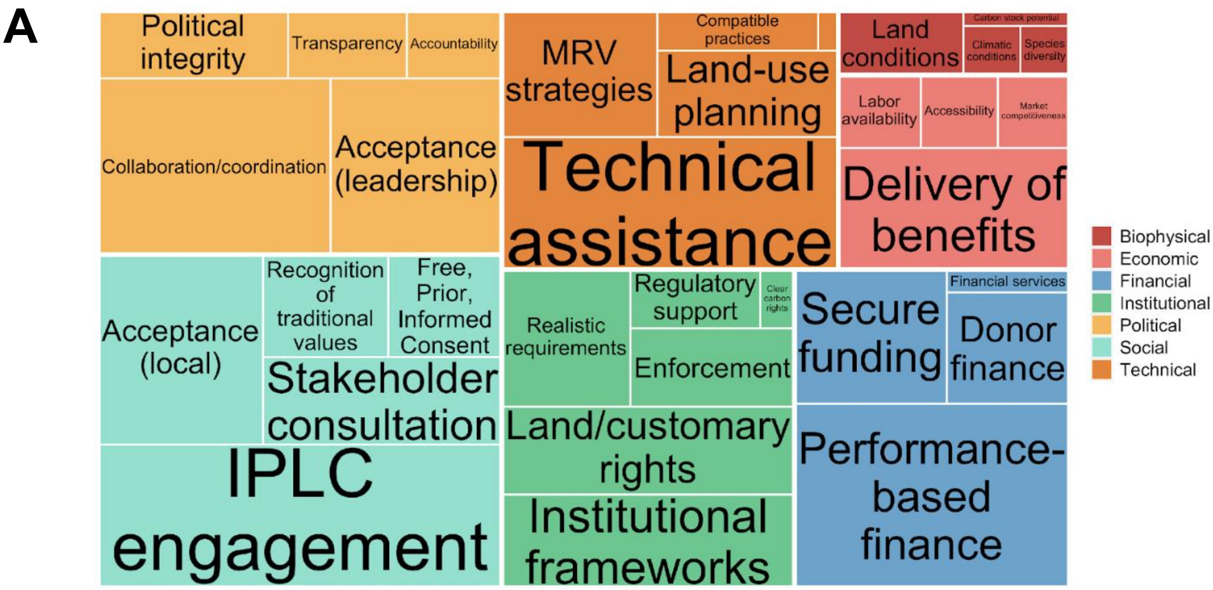
Wetland. We identified NCS activities related to wetlands – including coastal lands, peatlands, and rivers – in 8% of our observations (n=20). Half of these included mentions of wetland restoration generally (n=10). Three of these observations were from the same study on blue carbon that provided information on multiple countries (Wylie et al., 2016). Eight observations were identified for peatlands (avoided impacts, restoration, or both), five for river restoration (e.g., riparian and catchment areas), and two for coasts (avoided impacts, restoration, or both).

Four of the observations on river and wetland restoration were on the United States. Other countries captured in the observations for those activities were Costa Rica, Ethiopia, India, Kenya, Vietnam, Madagascar, and Indonesia with one each. In addition, half of the observations on peatland activities were on Indonesia (n=4), one on the United Kingdom, and one on Germany. The other two had regional foci on the EUR and North America. The studies on the developed countries centered more on peat restoration and management than the Indonesia literature, which also acknowledge efforts to avoid conversion of new peatland areas (Hagen et al., 2013; Mulyani & Jepson, 2017; Whitfield et al., 2011). Regarding the coastal activities, one observation was in the same study on the EUR that also mentioned peatland activities, while the other observation was on Sri Lanka. The latter is one of the few observations on mangroves (Tanaka, 2009).

4.2 What are important enabling factors and where?

In our global dataset, social and political enabling factors were mentioned most frequently on aggregate. These were closely followed by financial, institutional, and technical factors (**Figures 1.5 and 1.6**). Specifically, the engagement of indigenous peoples and local communities (IPLC), performance-based finance, and technical assistance are important drivers of NCS implementation. These factors are often overarching and interact with others, creating feedback effects (Aganyira et al., 2019; Dawson et al., 2018; Rosa da Conceição et al., 2018). Details for each NCS category and examples are provided in the subsequent subsections to illustrate our results.

Enabling factors appearing within each NCS category parallel the general trends in our dataset (**Figure 1.6**). The management literature had the most mentions for many factors and the protection literature the least, likely reflecting the difference in the number of observations between the two. Interestingly, free, prior, and informed consent (FPIC), stakeholder consultation, acceptance from leadership, and realistic requirements were factors that came up more often in the protection literature than other categories. This may possibly be because of the politicized nature of REDD+ or the tensions of setting legal destinations for conservation. For instance, many protected areas overlap with land traditionally used by local peoples for livelihoods. NCS in these areas has not led to positive outcomes, in particular when IPLCS do not have secure rights or access to grievance mechanisms (Tauli-Corpuz et al., 2020).



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Social

IPLC engagement	60%
Acceptance (local)	33%
Stakeholder consultation	22%
Recognition of traditional values	13%
Free, prior, informed, consent (FPIC)	12%

Economic

Delivery of benefits	29%
Accessibility	6%
Labor availability	6%
Market competitiveness	5%

Political

Collaboration/coordination	43%
Acceptance (leadership)	31%
Political integrity	13%
Transparency	8%
Accountability	7%

Institutional

Institutional frameworks	28%
Land/customary rights	27%
Realistic requirements	18%
Enforcement	13%
Regulatory support	8%
Clear carbon rights	2%

Financial

Performance-based finance	53%
Secure funding	21%
Donor finance	14%
Financial services	3%

Technical

Technical assistance	46%
Monitoring, reporting, verification	20%
Land-use planning	16%
Compatible practices	7%
Research	1%

Biophysical

Land conditions	8%
Climatic conditions	3%
Species diversity	3%
Carbon stock potential	2%

Figure 1.5. Distribution of NCS enabling factors in the literature. (A) Treemap illustrating the distribution of enabling factors extracted from the literature (N=1396 mentions in 240 observations). (B) Enabling factors by mentions in percent of the literature (N=240 observations in 211 studies) (see **Appendix** for icon image credits).

Factors such as delivery of benefits, labor availability, technical assistance, and performance-based finance were mentioned more in the restoration and management literature, even compared to other factors within those categories. Local acceptance and IPLC engagement were mentioned often in the management literature in particular. This may highlight on the one hand, the implementation costs and capacities needed to transition to sustainable land use practices but also the trade-offs that may make the willingness to participate in NCS activities from local actors challenging. Secure funding was mentioned most frequently in the restoration literature, which makes sense given that restoration activities may take more time to get off the ground and produce tangible results.

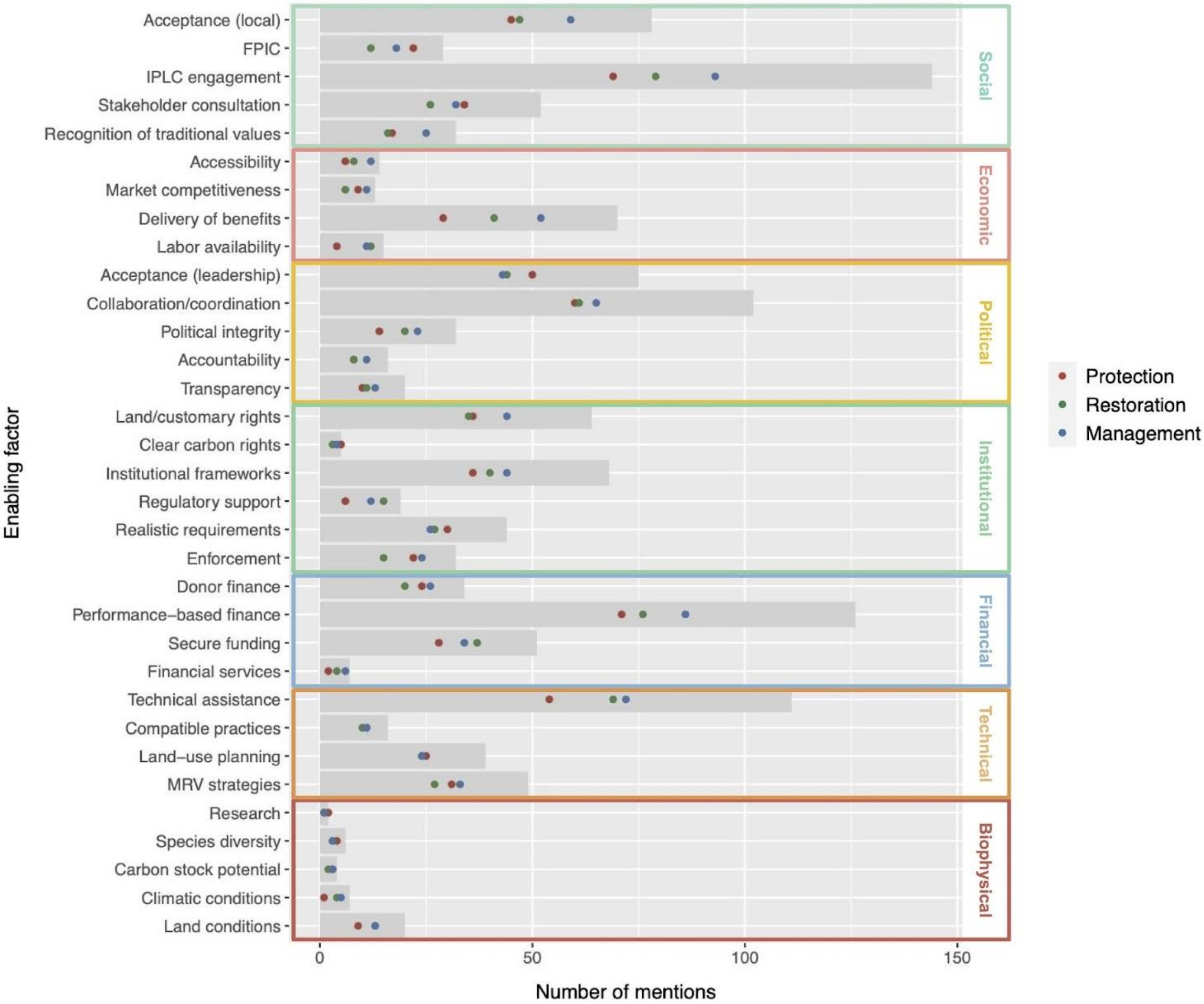

Figure 1.6. Mentions of enabling factors in the literature, including total number of mentions across all articles (in grey) and number of times mentioned in the literature on each category of natural climate solutions (protection, restoration, or management) (N=240 observations in 211 studies). Some articles mention multiple categories of NCS, thus there may be overlap in the mentions noted for the literature by NCS category.

4.2.1 Social

Of all the enabling factors identified in the literature, IPLC engagement was by far the factor that appeared in the most observations, present in 60% (n=144). Nearly half (48%, n=69 of 144) of these observations that mentioned IPLC engagement as an important factor included REDD+ projects or programs as a focus. Social safeguards, including the full and effective participation of IPLCs, are a requirement for REDD+ eligibility. A sub-sample analysis of this factor shows mentions of "participation of IPLCs" (n=115), "local awareness" (n=59), and "education" (n=50). In some observations, two or three of these were mentioned together. However, it is important to recognize the differences in each of these terms of engagement and how they relate to each other (see section **5.1**).

Local acceptance, where a consistent quality of life is ensured, community needs and benefits are aligned, and there is support for NCS activities, was another social factor we coded for. It was mentioned in 33% of observations (n=78). Free, prior, and informed consent, another concept along the line of participation but more complex, appeared in 12% of observations (n=29). It sets out principles for engaging indigenous peoples that have been adopted by many international organizations, including the United Nations during recent climate negotiations (Wallbott & Florian-Rivero, 2018). The element of consent is fundamental, as this is what sets FPIC apart from other consultation processes. It also goes beyond general stakeholder consultation, which we understood to also include outreach to different actor groups such as government, academia, and civil society (n=52). Nevertheless, these processes and inclusion criteria are meaningless if they do not account for local ways of life (Dawson et al., 2018; Duker et al., 2018). This recognition of traditional values and local norms was discussed in 13% of observations (n=32).

4.2.2 Economic

The most mentioned economic factor in our review was the delivery of benefits (n=70). In observations on Ethiopia and Indonesia, for example, researchers noted that project implementation was hampered due to a mismatch or insufficient benefits (Duker et al., 2018). In the latter, while people earned wages from tree planting and received training to support forest conservation, these did not compensate for losses on banned agricultural activities or meet farmers' livelihoods needs. In Vietnam, on the other hand, increased mangrove cover positively impacted farmers' shrimp production and income, making participating in restoration activities an attractive option (Wylie et al., 2016).

Labor availability, accessibility, and market competitiveness were also mentioned in a handful of observations (n=15, n=14, n=13, respectively). Some observations described limitations to implementation due to lack of qualified labor, in particular within project or program offices or responsible government ministries (Aganyira et al., 2019; Wurtzebach et al., 2019). Hein et al. (2018) highlight these shortages as a disconnect between priorities and resource allocation at district and national levels. In addition, difficulty accessing an activity site and weak demand for sustainable products posed barriers to NCS implementation (Bastos Lima et al., 2017; Huang et al., 2019; Muttaqin et al., 2019).

4.2.3 Political

Collaboration and coordination were mentioned as enabling factors for NCS implementation in 43% of observations (n=102). We understood this factor to include measures such as policy coordination between sectors or within a sector and alignment between standards and laws or laws at different levels, among others. This was followed by acceptance from leadership, i.e., political will, in a third of observations (31%, n=75), and integrity, accountability, and transparency (n=32, n=20, n=16, respectively). We included measures like lack of corruption and proper management under integrity, while having clearly designated responsibilities and authorities as well as access to justice were included under accountability.

4.2.4 Institutional

Strong frameworks to support NCS implementation were discussed as an enabling factor in 28% (n=68) of observations. Regulatory support, specifically, came up in 8% (n=19). Equally as important as these frameworks was clarity on land and customary rights (27%, n=64). Carbon rights were explicitly mentioned in just 2% of observations (n=5). We included various forms of security, recognition, and property types under the land and customary rights factor, such as both traditionally and legally-held ownership. These were, however, not always aligned with each other (Dawson et al., 2018). Availability and access to conflict resolution mechanisms for tenure can help ease these tensions (Holmes et al., 2017). Access to justice and grievance mechanisms are essential for ensuring equity and representation of IPLC perspectives in NCS activities.

Realistic program or project requirements were also mentioned as an enabling factor in 18% of observations (n=44) and enforcement in 13% (n= 32). Overly complex regulations, for example, tended to increase costs and be technically infeasible (Chia et al., 2019). Inadequate enforcement was cited as one reason for slow progress in some programs and projects. The ability to properly enforce policies and laws was often contingent on labor availability and technical capacity (Aganyira et al., 2019; Ngendakumana et al., 2017; Schroth et al., 2016; Wurtzebach et al., 2019).

4.2.5 Financial

Over half of our observations (53%, n=126) mention the role performance-based finance, or finance paid for demonstrated results, in many NCS programs or projects. This can take the form of payments for ecosystem services (PES) (n=65), where "providers" of clean air, water, and other healthy ecosystem services are compensated for their actions; benefits-sharing mechanisms (n=24), which aim to ensure that benefits received are equitably distributed to participating groups of people or communities; or results-based finance (n=23), in which program or project participants are paid for emissions reductions. The caveat was often that the incentives need to be appropriate to the local context (n=68) and payments have to be enough to maintain a consistent quality of life for IPLCs changing their practices and engaging in new activities (Duker et al., 2018).

There are also concerns about the lack of secure funding surrounding NCS activities. Ensuring a source of secure, long-term finance was mentioned as an important factor for successful, lasting, implementation in 21% of observations (n=51). Access to other financial services, such as local crediting schemes, received less attention in our dataset (n=7). Subsidies for NCS activities in many countries remain less than those to drivers of land use change (Bastos Lima et al., 2017; Regina et al., 2016). Tensions may also arise from external finance being uncertain, temporary, or acting as a competing investment. Some payment schemes also only support community projects rather than individuals, which was not well-received by community members in an example from Ethiopia (Duker et al., 2018).

4.2.6 Technical

Technical assistance was mentioned as an enabling factor in nearly half of the observations in our dataset (46%, n=111). Of these, 67% specifically include training, 31% information provision, 15% availability of seeds and seedlings, 12% adequate capacities, and 7% technology accessibility (n=74 of 111, n=35, n=17, n=13, n=8, respectively). Studies either described a lack of this assistance as a challenge, or found that farmers receiving technical support were more likely to move forward with implementation (Korhonen-Kurki et al., 2016; Wang et al., 2019). In China, this also provided a better understanding of the structure and composition of natural forest, which enabled better project design (Jiang et al., 2018). Training local people also filled labor needs.

Monitoring, reporting, and verification (MRV) was discussed in 20% of observations (n=49). Good MRV was contingent on available resources, such as technological or labor capacities. Community-based monitoring approaches also were used to build participation and ownership for projects among IPLCs (Newton et al., 2015; Rosa da Conceição et al., 2018). Land-use planning – mapping, identification of land-use drivers, and assessment of ecological conditions – came up almost as often as MRV (n=39). Planning prior to project or program activities can aid implementation, in particular in the long-term (Blomley et al., 2017; Mulyani & Jepson, 2017). Ensuring compatible practices or adoption of integrated approaches were a consideration in 7% of observations (n=16). Only two observations included research as a potential enabling factor.

With technical factors, there were also distributional imbalances reported. An analysis of participatory forest management in Tanzania found that training and information provision is given only to a certain number of people, who do not always pass this knowledge onto the community because they perceive there is no benefit to them or they cannot afford to (Mustalahti & Tassa, 2012). A study on payments for environmental services in Costa Rica also notes a lack of an effective monitoring system and that the design did not include small properties and some of the poorest households (Wallbott et al., 2019).

4.2.7 Biophysical

Few biophysical factors were discussed as enabling factors in the literature reviewed. This is likely due to our exclusion criteria, which removed any studies that focused on more technical and ecological aspects of how to do implementation. In our dataset, which really emphasized the enabling context for NCS activities, land conditions appeared the most, in 8% of observations (n=20). For example, where and what NCS activity was implemented could depend on the size of a project area or nature reserve, the surrounding land use, or the forest or land yield (Nolte et al., 2017; Shrestha et al., 2017). Climatic conditions (i.e., rainfall, adequate soil) were a factor in seven observations, species diversity in six, and the potential for increasing carbon stocks in four.

4.2.8 Co-benefits

The multiple potential outcomes of NCS activities are reflected in the co-benefits mentioned in the literature (**Figure 1.7**). Supporting local livelihoods was an important co-benefit and additional motivation for adopting NCS in 31% of observations (n=75). The value to biodiversity conservation was recognized in 22% (n=52) and carbon sequestration in 20% (n=47), the latter while also being a primary objective of NCS. Other co-benefits, such as community capacity building (n=21) and community rights (n=9), did not often explicitly appear as such in the literature. They are also more strongly represented in the dataset as enabling factors, or pre-conditions for implementation rather than outcomes.

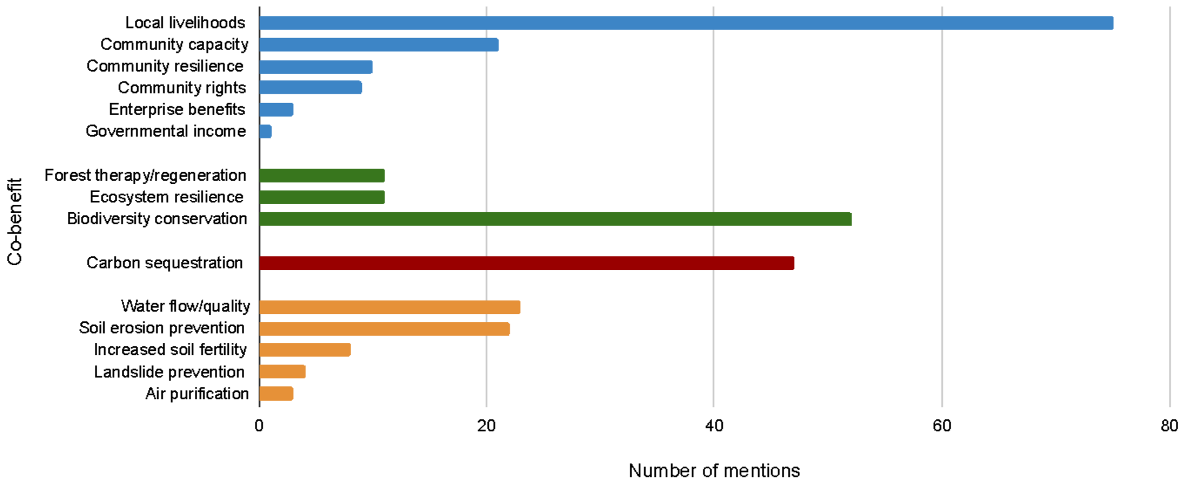

Figure 1.7. Number of mentions of co-benefits in the literature (N=240 observations in 211 studies). Co-benefits were discussed in the literature as potential outcomes of NCS activities, as opposed to pre-conditions for implementation, which were coded as enabling factors.

4.2.9 By geography

The overall distribution of enabling factors synthesized by region is similar to the global results. To add nuance, we looked at the distribution of enabling factors by category in the ten countries with the highest number of observations in our dataset (**Figure 1.8**). Social factors were most prominently mentioned in India, Nepal, China, Indonesia, Vietnam and Tanzania. In China, political factors comprised an equal share of mentions. The categories of factors mentioned in the United States were relatively evenly distributed, with biophysical and economic factors being mentioned the least. These categories, however, also had less factors than the others. In Mexico, Brazil, and Cameroon, institutional factors comprised the largest share of mentions. At the same time, the number one enabling factor mentioned in almost all ten countries was either performance-based finance or IPLC engagement. The exceptions were China and Cameroon, where local acceptance was mentioned the most, closely followed by performance-based finance;

and Mexico, where technical assistance was first followed by IPLC engagement. Other factors that received within the three highest mentions in these ten countries included collaboration and coordination, delivery of benefits, secure funding, and political integrity.

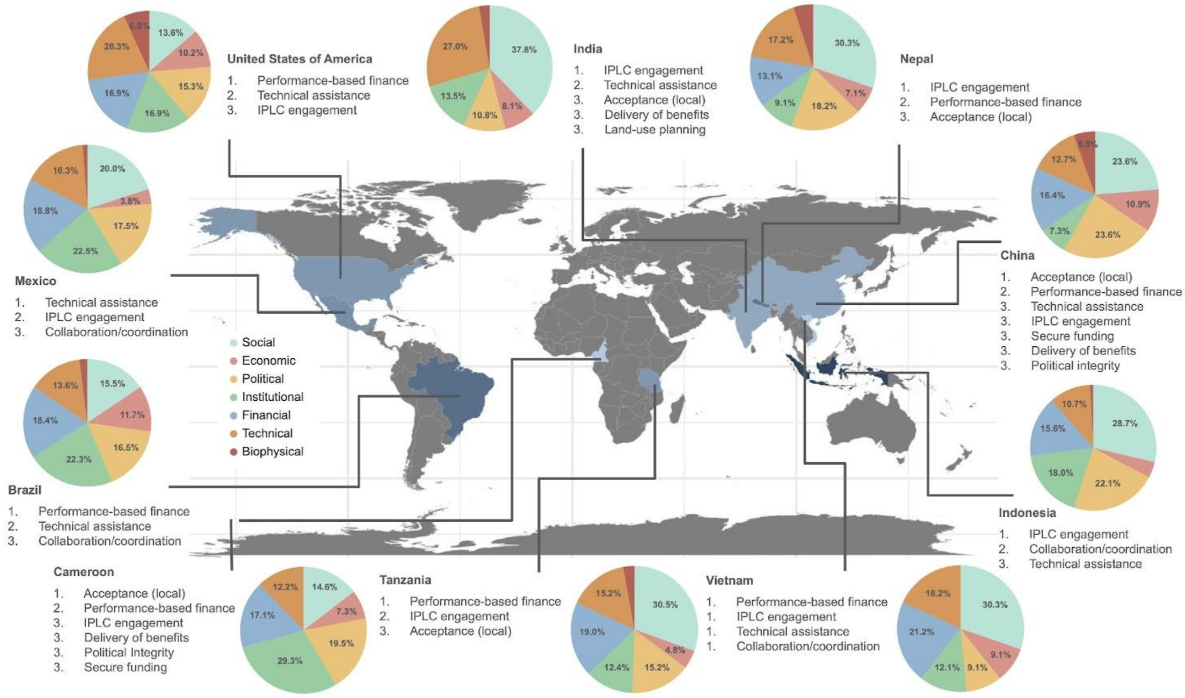

Figure 1.8. Enabling factors in ten countries. Shares of types of enabling factors and top three enabling factors mentioned in the literature on the ten countries with highest number of observations. More than three enabling factors are listed for countries where multiple factors are tied for a position. The position is indicated by the numbering.

5. Discussion

This section consists of four subsections: a short summary of our results and additional insights on the findings; building on our results; a discussion on how different enabling factors may fit together, or be “bundled”; a critical reflection on the current state of evidence and knowledge production for implementation of NCS; and concluding thoughts.

5.1 Summary and insights

This review provides an overview of the evidence base surrounding the implementation of NCS activities. We find the coverage of the studies skews towards tropical regions and activities in forest landscapes. Nevertheless, much can be learned about the enabling factors for implementation of NCS from the available data. These factors are often interlinked across categories (e.g., social, political, etc.) with engagement of indigenous peoples and local communities (IPLC), performance-based finance, and technical assistance being most frequently mentioned in the peer-reviewed literature.

We also observe that there remain challenges to ensuring enabling factors in practice. Projects sometimes take years to get off the ground or provide tangible benefits due to insecure finance or poor governance, leaving some communities feeling abandoned or skeptical of future promises (Enrici & Hubacek, 2019). Public perception is also a critical part of the implementation context (Wang et al., 2019). Lack of trust and confidence in project developers can amplify conflicts (Duker et al., 2018). In a case in India, local leaders were elected by the community and committees democratically decided what sustainable livelihood activities to support (Chowdhury et al., 2016). This type of approach is particularly relevant to community forest management and participatory forest management activities where better integration of IPLCs is needed (Cronkleton et al., 2011; Mustalahti & Tassa, 2012).

The findings of the reviewed literature also suggest that participation cannot be effective without awareness. Awareness can come about through education, dialogue, or an existing connection to the land. The latter was the case with farmers living in earthquake-stricken areas of China, where their experiences made them more aware of the importance of ecological protection (Gong & Zeng, 2019). Furthermore, awareness can strengthen the longevity of NCS activities by promoting buy-in among IPLCs. Evidence on the United States, for example, indicates that forest owners who were aware of climate change were more willing to participate in NCS activities (Charnley et al., 2010; Tian et al., 2015). Additionally, research from Costa Rica and Cambodia found wealthier households and farmers were more willing to participate in NCS activities, raising questions about equity (Cole, 2010; Pasgaard, 2015). This is supported by a study on the Asia-Pacific region that notes that REDD+ participation is limited and exclusion of the poor and insecure tenure rights remain a problem (Barr & Sayer, 2012).

Many studies in the reviewed literature also discussed the role of regulatory support for implementation and how it could be streamlined. For example, REDD+ frameworks or any new institutional arrangements need to either be consistent with existing laws or embedded into them (Korhonen-Kurki et al., 2016). If there are too many institutions, this also risks leading to regulations and tenure overlapping, conflicting government priorities, and confusion over laws (Enrici & Hubacek, 2019).

Political factors often appeared together in the literature, together with institutional factors. Poor leadership often resulted in poor coordination between vertically and horizontally, unclear authority, weak enforcement, lack of policy consistency, and overlapping or misaligned regulations (Chia et al., 2019; Korhonen-Kurki et al., 2016; Rosa da Conceição et al., 2018). Implementation was also limited with NCS activities where not a priority for those in power, where decisions were made with short-term objectives in mind, or those in power did not have the technical expertise needed to participate fully in the REDD+ process but continued to do so for political reasons. This is also seen with international actors who often control national processes due either financial or political influence (Dawson et al., 2018).

In addition, interventions such as payments for ecosystem services can also be difficult to implement if other enabling factors, such as clear land tenure, are not in place (Cortner et al., 2019). Results-based payments and benefit-sharing, for example in connection to REDD+, have been touted for their potential to provide long-term funding through access to markets for carbon credits. These programs often depend on donor finance (n=34) to be set up, however. Governments are also major driving forces behind REDD+ and other PES programs, but effectiveness can be low due to political obstacles (Rosa da Conceição et al., 2018).

5.2 Bundling enabling factors

Our results highlight that the successful implementation of NCS rely, not on one factor, but a suite of enabling factors. Individual factors may also open doors to capitalize on other enabling factors along implementation pathways. For example, recognition of traditional values may lead to greater acceptance of NCS activities by local communities. Based on the evidence in our review synthesis, we present three illustrative pathways by considering enabling factors that may interact with each other in different contexts (**Figure 1.9**). We outline our proposed pathways below and describe characteristics of each. While implementation trajectories are not limited to these pathways and they are not mutually exclusive, we see these as a useful heuristic for thinking holistically about the conditionality and variability of NCS implementation and informing policy discussions.

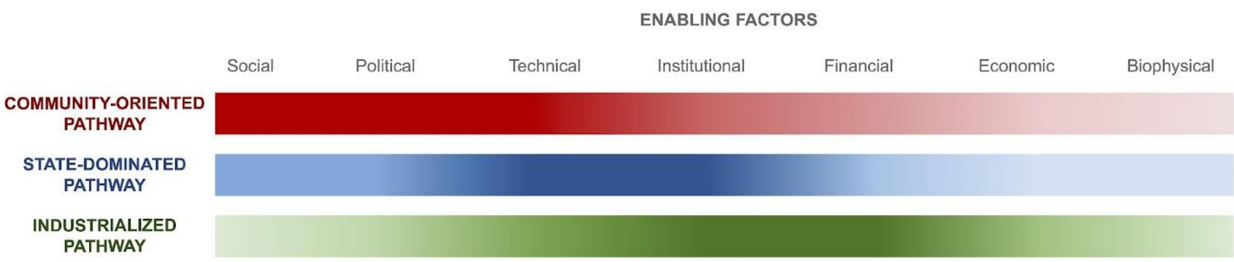

Figure 1.9. Illustrative implementation pathways. Darker colors indicate categories of enabling factors that may play a larger role in implementation for each pathway. These pathways are meant to serve as examples to show that there are different combinations of factors that may influence implementation, and these are highly context dependent. Implementation trajectories are not limited to these pathways and they are not mutually exclusive.

5.2.1 State-dominated pathway

Countries or geographies falling into the state-dominated pathway may include those where governments hold strong influence and control, but experience weak governance due to lack of leadership, corruption, and conflicting priorities between decision makers. Land use planning and consideration of NCS is a top-down process. At the same time, these countries have large local and vulnerable populations that depend on natural ecosystems for their livelihoods but face difficulties in having their needs met. Certain activities, such as cattle ranching, may also be socially and culturally embedded adding extra complexity (Cortner et al., 2019). Examples include case studies from parts of Brazil, China, Vietnam, and Uganda (Cortner et al., 2019; Dawson et al., 2018; Wang et al., 2019; Wurtzebach et al., 2019).

In the state-dominated pathway, we argue that social and political factors represent particularly foundational stepping stones for implementing NCS potential. This may be due to bottlenecks posed by political insecurity and changing priorities, which can lead to mistrust of the government among farmers and local communities (Cortner et al., 2019). The politics of the moment may also drive institutional and financial decisions that may have trickle down effects on NCS implementation. For instance, in Ecuador electoral interests led to prioritization of non-environmental concerns and overall low conservation effectiveness in the national sustainable forest management program (Rosa da Conceição et al., 2018).

Various other challenges are also described in the literature, such as pro-environment and IPLC policies being anchored in laws, but often ignored (Baez, 2011). In Peru, officials disregarded a consultation process because they felt it was more important to get the program deployed quickly, leading to adverse outcomes (Rosa da Conceição et al., 2018). As such, coordination and collaboration between different levels of government and stakeholders, as well as integrity, accountability, transparency and enforcement mechanisms are essential. These factors are also necessary to close gaps and increase communication between policy makers and local people (Wang et al., 2019). At the same time, leveraging existing policies and institutions are a first step in realizing them and improving learning (Wurtzebach et al., 2019).

5.2.2 Community-oriented pathway

The community-oriented pathway is characterized by a strong political and social interest in participatory land management approaches. Underlying these approaches, however, are financial and technical considerations that are often the limiting factors for implementation. Also important are social factors, in particular acceptance of NCS activities by the local communities and people that are expected to partake. Examples of places employing community or social forestry and land management programs include cases from Indonesia, Nepal, Ethiopia, Panama, and Tanzania, but also Brazil highlighting overlaps between and the fluidity of our proposed pathways (Cronkleton et al., 2011; Duker et al., 2018; Holmes et al., 2017; Newton et al., 2015; Wood et al., 2019).

Duker et al. (2018) describe how the lack of engagement of smallholder farmers in the development of climate forestry projects in Ethiopia and Indonesia led to distrust, which was amplified by insufficient and unreliable incentives for farmers to participate in conservation. An additional study in Ethiopia observed a community forest management approach with overall positive impacts on the land, carbon and biodiversity; however, this took place over a longer period (Wood et al., 2019). Collaboration between communities and the government and reaching a common understanding, for example, took ten years to establish. In other cases, discourses are still shaped by a small group of powerful actors in practice (Bushley, 2014).

In this pathway, institutional factors remain relevant and strongly interact with social and political factors. Local support for an NCS activity, for example, is often linked to clear land or forest rights for communities (Wood et al., 2019). In Tanzania and Nepal, an important reason for success in their community-based forestry programs was that they had existing institutional structures and laws in place which they could build on through REDD+ readiness activities, so the frameworks and political will for implementation were already present (Newton et al., 2015).

5.2.3 Industrialized pathway

The industrialized pathway reflects a way forward for developed countries or geographies that may have the institutional structures already in place to support NCS implementation, but still face challenges in meeting diverse stakeholder needs and providing sufficient incentives for actors to shift away from their potentially unsustainable business-as-usual practices. Examples of such countries from the literature include the United States, Germany, and the United Kingdom (Feliciano et al., 2014; Schaich & Plieninger, 2013; Schmitz & Kelly, 2016).

In particular in the context of emerging carbon markets, countries may struggle to balance diverging land management approaches from vested-interest actor groups aiming to maximize carbon sequestration versus conservation-minded stakeholders concerned that "carbon farming" may result in trade-offs for ecological integrity (Schmitz & Kelly, 2016). Similar to in the other pathways, performance-based finance and technical assistance also are relevant to sustainable land management. Land in these countries is often under a combination of public and private ownership that demands diverse approaches for shifting the behavior of land users (Schaich & Plieninger, 2013). In addition to market mechanisms, incentives may take the form of direct public payments for ecosystem services or tax subsidies and exemptions (Tian et al., 2015). Attitudes of private landowners towards these incentives may vary based on their interests and experiences with them.

5.3 Critical reflection and implications for the future

Our review results and illustrative pathways (see section **5.2**) highlight that there is not a one-size fits all approach for implementing NCS. While the broad categories of factors mentioned in the literature are similar across regions, the combination of factors and how and for whom they are taken up remains heterogeneous globally, and even within countries. This points to the importance and need to reflect critically on current policy discourses and narratives. This is relevant to the identification of research and knowledge gaps as well as deciding how to implement activities and measure if they are effective. Below, we discuss these gaps as well as considerations for future knowledge production.

5.3.1 Research gaps

While our study focuses on NCS, taking climate change mitigation as the primary objective, it is important that NCS activities not be designed with only this objective in mind. Based on the evidence in our review, we observe that local livelihoods and biodiversity are mentioned most frequently as co-benefits. In line with Girardin et al. (2021), recognizing these factors not only as co-benefits, but co-objectives from the outset, is central to the long term, ethical, and equitable implementation of NCS. More interdisciplinary research is needed here to avoid silos, but these types of publications were clearly lacking within our database. We were able to capture projects that did not mention climate or carbon as the explicit focus, but where it could be understood as an important co-objective (e.g., projects with a community-based conservation frame), due to the nature of our search query. However, few articles reported on carbon and other greenhouse gas outcomes together with social outcomes.

The bias in the literature towards forest landscapes also demonstrates the difficulty of providing a representative set of information on NCS to policymakers. Generally, there was a lack of on the ground research on different ecosystems. There were a number of papers on grasslands in China and Mongolia that we excluded because they projected scenario outcomes of NCS activities but did not provide evidence on implementation drivers. While our review results between landscapes were similar enough to indicate we can learn about the implementation context of NCS across ecosystems from others, this lack of balanced evidence on different types of NCS can have other implications. One risk is that it unintentionally trickles down in project and research funding decisions, influencing the direction of future workstreams. Lack of information may also slow or hamper implementation all together. The opposite can also occur, as demonstrated by the trend we observe with the development of REDD+, subsequent policy and financing mechanisms, and the publications that followed.

There were also major research gaps on particular geographies. We found few publications on Oceania, for example. Though a small region, it is a vulnerable area and uptake of NCS, including wetland protection and restoration, could improve resilience to future climate events by providing both climate change mitigation and adaptation benefits. More research, however, is needed on countries in the area to determine the feasibility and approach for implementing such activities. Other areas may be underresearched because they are challenging to access due to political tensions, civil unrest, lack of established contacts, or difficult terrain. In practice, research locations are often determined by the scope of funding schemes or network entry points. We also acknowledge that a limitation of our study is that it excluded publications outside the English language. It is possible that we would find more information on regions such as West Africa and East Asia if we ran our search query in the French or Chinese languages. More exploration of virtual research methods could be useful for eliciting broader input and negating some of these structural biases. These limitations do not diminish our results, but are important to highlight for the sake of transparency and identifying future research opportunities.

In addition, our review did not include information from project databases or grey literature. These may provide further information on NCS implementation, but may come with their own biases if only certain information is included to meet reporting requirements or selection of project areas is influenced by donor interests. At the same, the IPCC is also limited to peer-reviewed literature and coverage of social sciences remains patchy. Social science studies, in particular of qualitative nature, have historically faced difficulties finding a home in the IPCC process due to concerns about them being too interpretive (Minx et al., 2017; Victor, 2015). This is slowly changing, and systematic methods and reviews such as ours are one channel for ensuring rigorous assessment of the available evidence. While synthesizing information from a diverse set of case studies is challenging and some interpretation by individual reviewers in the coding is unavoidable, having a clear protocol helps reduce those arbitrary decisions. In addition, it allows for future work to improve NCS activities to easily expand on our study. The literature on NCS is growing at a rapid pace and a large number of new articles on NCS activities have been published since initiating this review two years ago. This new body of literature could be evaluated against our results to potentially address some of the gaps we have raised.

5.3.2 Considerations for knowledge production

Finally, it is important to critically reflect on who is creating the evidence we are assessing and for whom. Western scientists and economists are the dominant influence in climate change research and policy processes, though with NCS much action is projected in non-Western countries. Our review can help us identify enablers of implementation in different places, but what is effective or successful implementation may depend on the activity, how well it is implemented, and how long it is implemented, and who sets the criteria for determining this. Recent evidence from Indonesia reinforces that current land use scenarios and policy development do not yet provide the benefits or income needed to support livelihoods while placing more burden on local actors to contribute to climate change mitigation, as was the case for many studies in our review dataset (Merten et al., 2021). While there was a range in the duration of the projects in the reviewed literature, many did have longer timeframes due to our focus on NCS activities that were underway or had already been implemented.

Thus, a different set of enabling factors may matter more when thinking about implementation from an alternative perspective, such as a social justice or equity angle, than purely a mitigation objective. These could include more focus on capacities of communities and smallholders, local land use rights, and participatory decision-making processes. These factors are typically excluded from the modelling projections that determine the potential for NCS to begin with because they are complex to integrate or data, if available, is considered to be inadequate. While it is difficult to ensure representativeness in research, applying the concept of "unlearning", or letting go of preconceived notions to allow for new knowledge to be created, may also be useful to explore within this framing and existing meta-narratives (Becker, 2005; Downes et al., 2015).

This raises the question, who informs and decides on the global NCS agenda. Similarly, who determines who should bear the costs of implementation? Undeniably, the positionality of researchers plays a role in the formation of the evidence base, the messaging of the results, and to whom it is disseminated. While beyond the scope of this paper, a mapping of authors and funding sources driving the research in our database would be valuable in identifying possible systemic biases and power imbalances.

5.4 Conclusion

This review and dataset have allowed us to go beyond the analysis of individual enabling factors to provide a larger picture of how these factors fit together. While this is a first step, it points to the need to think more systematically about this topic. Moving forward, more inclusive (and systematic) methodologies for considering underlying drivers of change in technical and economic studies of potential for enhancing decision making could be explored.

Finally, our results indicate that implementation is contingent on interactions between enabling factors, among the most prevalent being social and political. It is likely that the goals of natural climate solutions will not be achieved without broadening them to recognize that the dimensions and impacts of climate change vary across the globe, and successful mitigation solutions will be those that include different strategies targeted at a range of actor groups. Climate change is taking place in diverse social, economic, political, institutional, financial, technical and biophysical contexts and we must make understanding and balancing the enabling factors within these realms a priority in research and policy.

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IV.2 Towards integration? Considering social aspects with large-scale computational models for nature-based solutions

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Abstract

The importance of social drivers of climate change interventions, or social aspects, is currently underrepresented in computational modelling projections. These parameters are largely excluded from estimates of technical mitigation potential, feasibility, and tools such as integrated assessment models (IAMs) and other large-scale models that influence the development of climate policies and notable bodies like the Intergovernmental Panel on Climate Change. This paper contributes to calls being made from within the research community to address this gap and strengthen linkages between modelling practices and social science insights. Using nature-based solutions (NbS) as a framing, we present the results of a critical literature review and interviews with multidisciplinary experts reflecting on the current state of integration around IAMs and opportunities to better capture social aspects within large-scale modelling processes. Our findings confirm the need to incorporate social aspects in IAMs, but highlight that how this happens in practice may depend on context, project objectives, or pragmatic choices rather than conceptual notions about what 'good' integration is. Nevertheless, some integration strategies are better than others, and concerns about data limitations and low capacity of the IAM community for engaging in integration can be overcome with sufficient support and complementary efforts from the broader research community.

Keywords

integrated assessment models; large-scale models; nature-based solutions; climate change; social sciences and humanities

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Climate Change emphasizes that land-based climate change mitigation and emissions reductions are essential, alongside decarbonization of other sectors, to reaching climate targets and limiting global temperature rise (IPCC, 2019). Thus nature-based solutions (NbS) – actions by people that protect, restore, and strengthen natural ecosystems while addressing societal challenges – have received substantial attention as climate interventions with high mitigation and adaptation potential that also contribute to human well-being and biodiversity goals (Seddon et al., 2021). At the same time, estimates of the technical mitigation potential of these opportunities draw on global, macro-scale modelling with large uncertainties (Griscom et al., 2017), and estimating the socio-economic benefits and trade-offs is complex (Forster et al., 2020). Restoration, for example, holds large opportunities according to model results, yet research on the feasibility or potential is often limited to a techno-economic or biophysical assessment (Acosta et al., 2018).

As such, increasing attention is being given to the need to better consider social drivers of climate change interventions, or social aspects[6], in large-scale computational models such as the integrated assessment models (IAMs) dominating the climate pathways assessed by the IPCC (Costanza et al., 2007; Elsawah et al., 2015; Jewell & Cherp, 2020; Trutnevyte et al., 2019). IAMs, for example, are dynamic representations of coupled systems, including energy, land, economic and climate systems (Weyant, 2017). By combining knowledge on trends and emissions from these sectors, they can be used to make projections about the future and allow us to study the implications of different policies, primarily for climate change. Similarly, large-scale land-use models provide a framework for the assessment of anthropogenic and natural ecosystems at broad, often global, spatial scales (Munn, 2002).

IAMs have relatively crude representations of land use change, but are increasingly being paired with large-scale land use models to allow for higher granularity of analysis and assessment of associated trade-offs and opportunities. Such land-based IAMs are increasingly being used for national and regional-level assessments, where the need to include social aspects becomes even more apparent. This is demonstrated by recent literature reviews highlighting the variation in land-use decision-makers globally (Malek & Verburg, 2020) and the importance of social factors in the implementation of NbS (Schulte et al., 2022). The Intergovernmental Science-Policy Platform on

[6] See **Section 2.1** for a full conceptualization of the term “social aspects”.

Biodiversity and Ecosystem Services (IPBES) has even shifted to a new conceptual framework that puts culture at the forefront of the relationship between people and nature (Díaz et al., 2018).

At the same time, IAMs face a number of limitations. What is computationally feasible may not be on the ground, thus "feasible" model solutions are often not attainable in the real world (Riahi et al., 2015). Critics also argue it is too easy to generate and "validate" desired results (Beck & Krueger, 2016), in particular in the face of inevitable uncertainties and when it is only the modellers who make choices about scope, equations, parameter values, and output presentation (Pindyck, 2017). Critical reflection is needed on these choices and related power dynamics. Finally, IAMs generally do not account for equity and only represent the views of a subset of actors, e.g., those who align with the modellers' values and assumptions (Sonja & Harald, 2018). Yet, these are the ones that are then brought into the policy process, which risks marginalizing and excluding vulnerable groups. This further raises the need for more research on how diverse voices can be brought into the knowledge-making process and how models can better reflect underlying social drivers of climate change mitigation and adaptation decisions.

As such, this paper is guided by the following questions: (1) What is the current state of integration of social aspects and IAMs? and (2) What are opportunities to better include social aspects within large-scale modelling processes? We explore these questions using a critical literature review approach and information elicited from expert interviews with a two-fold aim to first, support a better understanding of integration dynamics within the IAM context that can be useful for researchers; and second, to identify entry points for diversifying perspectives along the modelling process to better inform the stakeholders that can benefit the most from well-balanced IAMs, such as national policymakers, multinational corporations, and international initiatives.

We focus on large-scale computational models, and IAMs in particular, because of the dominant role they have asserted in shaping climate policy and narratives. They have become an important source of information for decision-makers and influential scientific bodies such as the International Governmental Panel on Climate Change (IPCC) in particular, and there is no indication that this will change in the future. The estimated contribution of IAM results to the Fifth Assessment Report of the IPCC (2014) was double that of the First Assessment Report (1990) and the number of publications involving IAMs in the academic literature has exponentially increased over the past three decades (van Beek et al., 2020). In addition, Hughes & Paterson (2017) describe the shift in the IPCC from a body synthesizing knowledge on climate change to an authority on climate change stating "the IPCC is defining both the terms of climate change mitigation knowledge production and global political action*."* Beck & Mahony (2018) similarly note the influence of the IPCC on the climate policy agenda.

We focus on nature-based solutions to contribute to an underresearched, but valuable, area of land-use modelling. Nature has become a serious topic of discussion for climate mitigation and sustainable development in recent years and was one of the key themes at COP26 in the UK. More regional and country-level evaluations of contextual (i.e., non-biophysical and non-technological) factors alongside IAMs are necessary to provide more feasible assessments of opportunities and inform policy planning and options (Schulte et al., 2022). With NbS it is essential to reflect on multiple system interactions holistically, however, the literature on the interactions between social preferences and large-scale modelling to date has mostly targeted the energy domain and transport sector (Hirt et al., 2020; Krumm et al., 2022; Pettifor et al., 2017; Pye et al., 2021; Sovacool, 2014; Xexakis et al., 2020). Thus, our findings contribute to ongoing and increasingly urgent methodological and policy research agendas, given imminent threats of climate disasters, by illustrating the need and possibilities for social aspects with large-scale land-based models.

The remainder of this paper is structured as follows: **Section 2** outlines the conceptual framework; **Section 3** describes our methods; **Section 4** presents our findings; and **Section 5** discusses the implications and insights of our study.

2. Conceptual framework

Here we present the conceptual framework for this paper by defining what we mean by social aspects and integration for the purposes of this study. In addition, we present theories of participatory research, including ideas around reflexivity, validity, and co-production, which can be useful when thinking about how to implement integrative practices to capture social aspects. We use these concepts to guide our research, evaluate our results, and comment on the stages of scenario and model development, or what we refer to as the modelling process (**Figure 2.1**).

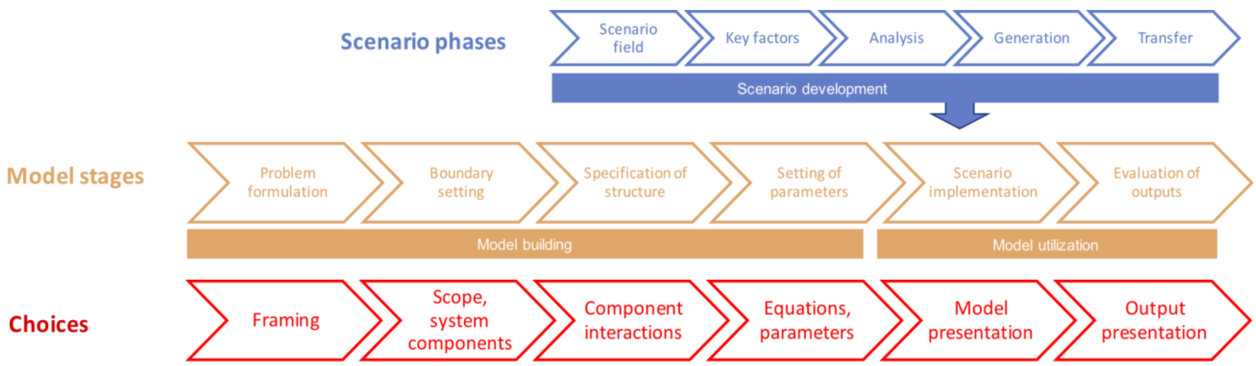

Figure 2.1. Simplified depiction of the modelling process (own illustration).

2.1 Defining social aspects

A large body of literature exists that is dedicated to social drivers of climate change. Jorgenson et al. (2019) review this literature and identify factors such as "economic conditions and development; demographic growth and changes; power, social stratification and inequality; technology; infrastructure; and land-use change" as major contributors to emissions. At the same time, these factors underlie people's responses to policies, potentially influencing how effective efforts are to address climate change and its impacts. Our use of the term of "social drivers" builds on this literature in that we focus on social drivers of mitigation and adaptation activities. Specifically, we are interested in factors in societies and characteristics of people that may influence the uptake of such activities – i.e., social drivers of climate change interventions.

For the purposes of this paper, we use terms such as "social drivers", "social aspects", "social preferences," and "social factors" interchangeably as these are all terms that have been previously used by authors in the modelling literature. In their research on energy models, Krumm et al. (2022), for example, define social aspects as "all aspects that concern the people, their interactions, and relationships within the energy system. [They] use the term as a synonym to social dimension and social factors." Similarly, Trutnevyte et al. (2019) discuss "societal factors" that are missing from models. Gerten et al. (2018) outline a set of "human dimensions" that should be considered in models, while Moore et al (2022) introduces these as "preferences".

Drawing from this compilation of literature, social aspects of particular interest for modelling are behavior and lifestyle choices, the heterogeneity of actors, public acceptance and opposition, public participation and ownership, and transformation dynamics. These are seen as major social processes driving socio-technical transitions (Krumm et al., 2022; Trutnevyte et al., 2019). These aspects can influence support or opposition to particular climate interventions or interactions between actors that may lead to cooperation or conflict. Specific social aspects where information is currently lacking in large-scale models include individual and collective behaviors, cultures, perceptions, and values (Gerten et al., 2018; Moore et al., 2022).

2.2 Understanding integration

When it comes to computational models, integration can refer to the technical linking of different models and model components or the inclusion of new elements in the modelling process. Much recent discourse around integration and IAMs has focused on the latter, in particular regarding social science research and models, in an attempt to bring more in social aspects (Krumm et al., 2022; Peng et al., 2021; Trutnevyte et al., 2019). An essential requirement for this type of integration is collaboration between researchers across disciplines. To facilitate such collaboration, Trutnevyte et al. (2019) propose three strategies that, in theory, allow for varying degrees of integration. We use these strategies – bridging, iterating, and merging – as reference points for our research on integration in large-scale modelling processes. The strategies are outlined in detail in the subsequent paragraphs.

Bridging analytical approaches is considered to be the most realistic strategy by many (Geels et al., 2016). This is not a novel approach, and arguably already commonly adopted, even if not formally recognized as such. This strategy consists of collaboration between modellers and social scientists where research occurs in parallel, with opportunities to come together to discuss ideas and promote mutual learning. Bridging these different disciplinary approaches via shared interests and concepts can present a more useful and complete analysis on a complex topic, for example when evaluating sustainability transitions pathways (Turnheim et al., 2015). This is applied by van Sluisveld et al. (2020), for example. The authors use shared concepts to bridge a multi-level perspective framework, which is used for analyzing socio-technical transitions, and integrated assessment models, by allowing researchers to weight qualitative case-study findings to derive inputs for the quantitative models.

Between the bridging and merging strategies is the iterating strategy. This strategy goes in the direction of approaches that already aim to bring qualitative and quantitative research together in the modelling process, such as the story-and-simulation approach. Here, narrative scenarios are combined with numerical modelling methods to analyze complex causal relationships (Kosow & Gassner, 2007). Social sciences can play an exogenous role in defining narratives, informing model assumptions, or interpreting model outputs. This strategy can be observed with IAMs and the shared socio-economic pathways (SSPs), which are narrative storylines that are used to inform model scenarios and assumptions (O'Neill et al., 2020). Nonetheless, there remains much methodological grey area around iterating strategies and their applications.

Merging is ambitious, but has been critiqued by some as problematic on a fundamental level for epistemic reasons (Geels et al., 2016; Spash, 2012) or undesirable because it detracts from deeper intellectual issues (Castree, 2014, 2015). It involves in-depth, structural modification to a model and assumes key social aspects can be modelled. Even if that were the case and the data was available, altering complex models such as IAMs – that are often developed over a number of years – would require time and effort that is challenging to undertake. Research on vehicle transitions by Pettifor et al. (2017) demonstrates how endogenous changes to IAM formulations that allow for the exploration of social influence and cultural variation do have a significant impact on the model results. However, this comes with caveats, such as the models still being stylized and cost-optimal solutions, rather than fully capturing behavioral realism, raising the question to what extent this is even possible.

2.3 Participation and knowledge production

The modelling process includes multiple stages that may involve different people. These stages are not always independent and there may be overlap between them. Furthermore, important choices are made at each step that shape the final model output. Thus participation in the modelling process is an essential part of influencing it and realizing integration. For that reason, when considering the integration of social aspects in particular, it is important to focus on participatory processes such as which actors are engaged at what points in the IAM modelling process, how, why, and who may still be left out. This is also useful for mapping the assumptions going into the model, analyzing how they relate to realities on-the-ground, and helping to identify model gaps.

Outlining theories of participatory research provides us a lens to look at the IAM modelling process. One definition describes participatory research "a process of sequential reflection and action, carried out with and by local people rather than on them" (Cornwall & Jewkes, 1995). As such, the rebalancing of power between the researcher and those researched on is seen as an important advantage of participatory research. Still, there is a lack of consensus around what this means and how it is executed. Arnstein (1969) first proposed a "ladder of citizen participation" that inspired a typology that included levels of passive participation, extraction of information, decision-support participation, interactive participation, and self-organization of participants (Pretty, 1995). This was later narrowed down by Lynam et al. (2007) to extractive use, co-learning, and co-management of knowledge for a decision-making process.

Similarly, Mayer (1997) outlined seven degrees of stakeholder participation in the policy analysis process, ranging from education and sharing of information, to consultation, anticipation, meditation, co-ordination, co-operation and co-production, and finally transformation and learning. Mayer's degrees of participation are non-linear, but do increase in complexity, or the engagement required from actors. In all cases, the mode or degree of participation is not fixed, and may evolve over the course of a research project. van der Riet (2008) points out that participatory research has the potential to "[access] the intentionality and sociality of human action; and [account] for contextualized and distanciated perspectives in the study of human action." The ontologies and epistemologies which the research is embedded in, however, may impact what information is obtained and its validity.

In line with the literature, we argue that there is no inherent greater value in one type of participation over another, but the degree of participation ultimately depends on the research and overall project objectives. Different degrees and combinations of citizen, stakeholder, and expert participation may be relevant at different stages of scenario and model development. Generally, participatory approaches are understood to strengthen the validity of knowledge created. Reflexivity is needed, however, to understand the boundaries of a participatory research approach, as even participatory processes can unintentionally exclude people. For example, if information is elicited from a community at a meeting only attended by men, this may not be representative of the community as a whole.

In the IAM context, there are varying views of what participation can look like and what gaps participatory approaches can address in models. Sonja & Harald (2018) discuss what elements should be included in IAMs to be able to better contribute to debates about the equity of climate policies. The elements they propose include context sensitivity, increased model responsiveness to user perspectives, and more focus on national modelling that reflects localized socio-economic concerns. Peng et al. (2021) also encourage stakeholders and politically-minded researchers to be consulted early in the IAM process and when considering model adjustments to ensure that reforms meet the needs of decision-makers.

3. Methods

This work is grounded in a critical literature review and complemented by expert interviews. Our evaluation relies primarily on insights from the literature, while the intention of the interviews was to solicit further perspectives and validate our review. We also elicited information on current thinking and discourses not yet published.

3.1 Critical review

We conducted an in-depth literature review on the topic of integration between social aspects and IAMs from June to August 2020. We followed the critical review approach outlined by Grant & Booth (2009), which draws on and evaluates existing literature but may include elements of conceptual innovation, reinterpretation, or resolution of competing ideas. There is "no formal requirement to present methods of the search, synthesis and analysis explicitly" as the emphasis is on the "conceptual contribution of each item" (Grant & Booth, 2009). Furthermore, an "effective critical review presents, analyses and synthesizes material from diverse sources." We determined this approach to be most appropriate for the purposes of this research because of the flexibility it allowed us to explore and bring together different bodies of literature. This literature then informed the conceptual framework of our study. In addition, applying a critical review approach challenged us to think creatively about how ideas and learnings we synthesized could potentially be applied across disciplines.

3.2 Expert interviews

We held twelve semi-structured video interviews with experts between August 2020 and March 2021, following guidance from Dunn (2010) and Longhurst (2010). We used the purposive sampling approach from Ritchie et al. (2003) for our selection of experts. A heterogeneous sample was chosen to ensure broad representation of perceptions and experiences. The reason for interviewing experts across disciplines was to understand diverse views on the potential for integration, but also applicability and policy-relevance (Flick, 2009). Specifically, we were interested in speaking to experts working in various capacities and scales along the modelling process (**Table 2.1**). As such our group of experts was quite multidisciplinary and included conceptual modellers, integrated assessment and large-scale modellers, system dynamicists, and ecologists. While disciplinary backgrounds are included in **Table 2.1**, it is worth noting that many interviewees have worked for many years in interdisciplinary contexts. The names and positions of the interviewees remain anonymous. Interviewees are instead referred to by a unique identifier, P1 to P12.

Table 2.1. Summary of expert interviewees

Participant	Background	Years of experience	IAM/Large-scale model experience?	Stakeholder experience?
P1	Policy analysis, energy	30 years	Constructing	Yes
P2	Ecology, system dynamics	20 years	Observing	Yes
P3	Ecology	30 years	Collaborating	Yes
P4	Physics, earth system sciences	10 years	Constructing	No
P5	Systems engineering, policy analysis, energy	9 years	Collaborating	Yes
P6	Anthropology, health	40+ years	No	Yes
P7	Geography, geoecology, environmental science	12 years	Observing	Yes
P8	Ecology	15 years	Constructing	Yes
P9	Natural resource management, system dynamics	40+ years	No	Yes
P10	Social sciences	14 years	Observing	Yes
P11	Climate change policy analysis, tropical ecology	15 years	No	Yes
P12	Policy analysis, energy, land use, earth system sciences	12 years	Constructing	Yes

We prepared guiding questions on the researchers' backgrounds, views on the role of social aspects in modelling, engagement with actors and stakeholders, and position on integration of societal information into the modelling process. Our questions were designed to provide vertical depth to the information elicited, starting from conceptual issues (e.g., objectives and ideal methods) to pragmatic research experience. The list of guiding questions can be found in the **Appendix**. Secondary, follow up questions were asked impromptu as appropriate (Dunn, 2010). We did not constrain ourselves to this list of questions, but adapted as necessary over the course of the interview to allow for a natural flow and create space for more narrative responses (Mason, 2004). Each interview was conducted in English and lasted about one hour. We took an interpretive stance for the interviews, meaning our objective was to understand and describe the viewpoints and experiences of different people and groups in real settings (Saldaña, 2015). All interviews were recorded. Following the interviews, information was summarized and key points were transcribed verbatim and coded inductively using MAXQDA.

4. Findings

In this section we present the findings of our review and answer our research questions. We evaluate the questions with our conceptual framework in mind and in tandem with contributions derived from our expert interviews.

4.1 Current state of integration of social aspects in IAMs

Shortcomings of IAMs that can be associated with limited integration of social aspects are widely acknowledged. IAMs primarily take into account economic costs, but do not fully address political feasibility (Jewell & Cherp, 2020). Furthermore, they tend to be ineffective at engaging policymakers and stakeholders in modelling activities, if it happens at all (Doukas et al., 2018). There remains little evidence in the literature on the integrated application of multiple methods in modelling, in particular around such issues (Elsawah et al., 2015). Interviewees familiar with IAMs also recognized the limits of their realism (P1, P4, P7). One noted "*there are parameters that are fixed in the models that we know are not in reality, such as the effect of climate change on rainfall or human behavior*" (P1). From a system dynamics perspective, another interviewee noted "*[these] feedbacks are important parts of a model because they affect what people do, and if left out this assumes they have an impact of zero*" (P9).

Overcoming these problems is essential when model-based scenarios are intended for policy making, as is increasingly the case with IAMs. For scientific activities to effectively contribute to climate policy design they must arguably fulfil three conditions (Doukas et al., 2018): (1) draw from combinations of diverse and complementary modelling tools; (2) adopt a "demand-driven approach" to modelling activities (e.g., problem formulation, definition of assumptions) that engages all relevant actors; and (3) include methodologies that can be linked with IAMs, which synthesize knowledge from a range of fields, to provide robust and replicable policy advice.

Calls for more integration between IAMs and social science methods have been the subject of ongoing academic discussion for decades. Easterling (1997) argues that an explicit mechanism was needed to engage stakeholders in the development of IAMs to ensure that their questions are answered and that they can actually use the information that IAMs provide them. Costanza et al. (2007) advocate for the development of more balanced, hybrid modelling approaches that bring together the natural and human aspects of socio-ecological systems. Similarly, Buck (2016) notes that evidence from the ground can provide insights on factors that biophysical and large-scale economic models may be lacking, such as social preferences or inequalities. Jewell & Cherp (2020) suggest that research on these gaps be guided by systematic frameworks. Trutnevyte et al. (2019) concretely capture these calls in a proposed research agenda "to guide experiments to integrate more insights from social sciences into models." Similarly, Peng et al. (2021) comment that an IAM reform is needed, to support decision makers in particular.

In practice, while there was general consensus among the interviewees that there is value to better understanding societal and social aspects that may be drivers of global change, one interviewee mentioned that "*overall demand for integration appears low from the modelling community*" (P4). Integrated assessment models are already doing an excellent job of linking different aspects of the economy with environmental and climate outcomes over long-term trajectories (P1, P4, P5). The community of researchers working on IAMs and other large-scale models is limited in size, though growing rapidly, and thus limited by the capacities of these modellers. Furthermore, many of them are prioritizing their resources working on relevant research to improve other aspects of the models.

Overall integration of the social sciences and integrated assessment models remains limited (Geels et al., 2016; Hirt et al., 2020). Our interviews confirm this, with experts citing lack of information such as political incentives, social preferences, and acceptance in large-scale models (P1, P3). Research on how to more effectively represent social issues in large-scale models is also at different stages for different sectors. Factors related to lifestyle changes, such as shifts in diets and consumption, and transportation have been paid more attention than nature-based solutions (Edelenbosch et al., 2018; Fuhrman et al., 2019; van den Berg et al., 2019). Nevertheless, modelling behavior is a challenge because "*you need numbers because those models only work with numbers [and] it's not easy to translate behavior into numbers*" (P1). Cost and opportunity costs are sometimes included as a feasibility layer and can be a proxy for immediate economic barriers to implementing a nature-based solution (P3). For example, if land has a high return and provides a large profit from agriculture, this poses a major challenge for converting it back into a natural ecosystem.

A number of reviews have explored approaches and methods for integrated modelling, but these are largely focused on quantifying human-Earth system feedbacks and few publications truly bring them together in an applied manner (Calvin & Bond-Lamberty, 2018). Müller-Hansen et al. (2017), for example, provide a comprehensive overview of techniques used to represent human behavior and decision-making in Earth system models; van Vuuren et al. (2012) discuss the strengths and weaknesses of various coupling approaches; Verburg et al. (2016) evaluate the abilities of current models to model Anthropocene dynamics; and Zvoleff & An (2014) present an overview of tools available for analyzing human-landscape interactions.

The interviews also indicate that there is a shift in the IAM community towards increased interdisciplinary collaboration. The modelling community has put significant effort into linking climate sciences and biodiversity sciences with economics; progress with the social sciences has been slower and some tensions and silos still remain (P1, P4, P10). In past decades policy and decision-making processes, and even the IPCC, were also more oriented towards economic disciplines and quantitative approaches over the social sciences (P4) (Minx et al., 2017). This highlights an important distinction to be made between "integrated" modelling in the context of those papers and "integration". Integrated models couple existing models so they can exchange information while integration aims for exchange between social science researchers and modellers throughout the modelling process. Far less research to date has focused on the latter.

Engaging stakeholders in the interpretation of results has been a common way of integrating social aspects in IAMs. The IAM community has tried and made strides to advance engagement with stakeholders to identify societal considerations through the shared socio-economic pathways. Efforts to expand global SSPs for local, regional, and national use have been ongoing and can provide useful insights on the role of participatory methods and stakeholder engagement in down-scaling large-scale scenarios. This is consistent with feedback from a number of interviewees mentioning interpretation of results as an area where there is linkage with the social sciences and topical experts may be called upon for input (P3, P6).

Chen et al. (2020), for example, draw on experts' opinions in workshops to identify important drivers of climate change futures in Japan. Frame et al. (2018) constructed and tested narratives with decision makers, stakeholders, and influencers in New Zealand. Similarly, for the Barents region in Russia, Nilsson et al. (2017) used SSPs to guide discussions and co-produce local narratives around future adaptation challenges and Absar & Preston (2015) extended SSPs for the Southeastern United States using a top-down method to create storyline elements for factors, actors, and sectors at the global, national, and subnational levels. These highlight the opportunities for iterative collaboration between modellers and social researchers to ensure that key dimensions, sufficient scalability, and widespread adoption are appropriately considered (Kriegler et al., 2012; O'Neill et al., 2014). Despite advancements in the downscaling of scenario development approaches for SSPs, many studies use arbitrary approaches to select and examine social aspects in IAMs, based on what the expert or modeller may be familiar with (Verburg et al., 2015; Voinov et al., 2018). This can generate dramatically different results between models.

At the same time, engaging external actors does not always lead to intended outcomes. This reiterates that engagement requires reflection on who is participating, when, and with what aim. In a project assessing various policy mixes, an interviewee reported that the consensus mix that came out of the stakeholder dialogue was quite weak; it would be feasible to implement, since there is agreement, but everything negative was left out, as was everything effective (P10). In another example, the participants of a workshop came to an agreement on the final product, but no one was really satisfied with it (P6).

4.2 Ways of enhancing the integration of social aspects in IAMs

Despite calls for integration, it remains unclear exactly how to do this. Some IAMs are top-down computable general equilibrium models, which look to historic macroeconomic trends such as impacts of changes in cost and price as indicators for the future. The issue here is that the past may not capture developments like technological advancements. Agent-based models (ABM) are one approach researchers are looking to for integration. ABMs are bottom-up models that can be extremely detailed for certain technologies and can see when there is a maximum gain in efficiency, but see less well how demand reacts. Moreover, as noted by an interviewee, these models "*are appropriate for a small scale and more specific questions than IAMs, which are intended to answer big picture questions*" (P1). Exploration of how to scale up agent-based models is ongoing and holds potential for introducing heterogeneity into large-scale models, particularly at the regional and national levels (Niamir et al., 2020).

Other researchers have suggested turning to social branches of economics such as behavioral, welfare, and political economics (Grubb et al., 2015; Mathias et al., 2020). However, this requires altering the models' methodologies and structure. This was also pointed out by an interviewee: "*deeply incorporating social dynamics and perspectives into IAMs would likely require rethinking some of the foundational economic theory and structure of these models*" (P4). These aspects are not captured in IAMs because they are difficult to model using existing methodological frameworks and may require numbers that are often not available. Without data, it is sometimes possible to determine a suitable proxy or rough substitute measure. Moreover, an important consideration for using societal data is that it must be reliable for it to make sense to include it in a model (P3). This means, if there are data sources and a dataset available and it does not change from year to year, then it might be possible to incorporate it.

Any degree of integration needs to consider path dependencies due to methodological consequences of IAM development. The importance of the design of IAMs was highlighted by two interviewees (P1, P9). The diversity of IAMs available illustrates how the choices made in the modelling process fully influence what the model outputs. The results of a model depend on the architecture of the model, including the sectors included and the level of detail. With small-scale models, it is more possible to start from scratch, and to engage local stakeholders early on to avoid shortcomings due to path dependency (P7). This is not necessarily always what is wanted, or needed for large-scale models (P1, P4, P5, P7).

Any model, large-scale models included, can only look like a function of the data they contain. No model is right or wrong, but due to inherent bias in their construction eventually they see different futures, which may have diverging policy implications. For example, most IAMs are linear programming models; they "*assume linear behaviours, and we know that that's not for sure*" (P1). Furthermore, "*they are not exactly dynamic in the sense that you feedback into your model things that already take a bit [of time]*" and "*we assume all consumers are rational*" (P1). This is why it is important to have a range of models that can be clustered and discussed with common scenarios as is the case in the IPCC assessment.

As such, it is important to be transparent about these models, what they can and cannot do, and how they are designed and carried out; and to do so in a way that is simple and accessible. According to our interviewees – experts who have experience informing, constructing, observing, and interpreting them – it is important to make clear that these models are not trying to forecast anything, but to ask "what if" and envision possible futures (P1, P2, P5). In doing so, researchers can present and instruct policymakers based on the possible implications of some decision that may be taken today, or in the medium or long-term, in particular across sectors (P1); in short, they try to show how sensitive the future is to these decisions.

Stakeholder engagement with clear objectives and appropriate degree of participation is important for integrating social aspects in IAMs. A higher degree of participation is necessary if modelling to design an intervention or project with a specific area in mind. For example, when it comes to the restoration and management of forests, it is essential to address pressures from adjacent communities (P8). Thus social acceptance and collaboration are key. This engagement is a co-development process. Stakeholders should be involved in the decision-making, implementation, and monitoring process; when they do not agree this may require conflict resolution and mediation (P3). It is also important to be clear about the limits of the research and uncertainties. Tools to simplify models and aid in discussions with stakeholders and their dissemination and accessibility can be useful here (P2, P3, P5, P7).

It is also important to recognize, however, that a high degree of participation has its limitations. Engagement may be constrained for pragmatic reasons; how researchers practice is often far from ideal due to time or resource bottlenecks (P2, P8, P10). How study participants are selected also often depends on who is willing to talk to you or where you have a connection. During COVID-19, for example, one interviewee was able to maintain his communications with stakeholders through a local researcher close to the field site (P2).

For this reason, there can be advantages to using data that is already available or modelling with a lower degree of participation. If there is value to building a relationship with land users for the study this should not be underestimated; however, if the study is a removed or larger-scale assessment, like IAMs, that will feed into something that may not impact them directly, it may be prudent to take the existing information and fill gaps as needed (P8). Given a lack of data, external actors can sometimes provide their perception or expert judgement of what data could be (i.e., provide a value for a parameter) (P1, P2). Stakeholders can also be sampled to collect data in a true participatory modelling approach; however, this is more ambitious and again requires additional time and resources (P6, P7).

A crucial caveat when engaging external actors, in particular local communities and stakeholders, is the need to manage expectations at the beginning of the project (P2, P8). There is a risk, for example, if stakeholders expect that you will bring investment or other benefits, they may distort the truth to gain more (P5). Interviewees noted when they succeeded in managing expectations, collaboration and brainstorming were more fruitful.

Beyond the IAM process, we find that systems dynamics and ecological modelling exercises often engage external actors, which we consider to be people that are not part of the internal research team. We do this because some interviewees mentioned that topical or "social science" experts may be engaged on socioeconomic aspects in modelling work, rather than reaching out to local citizens and stakeholders directly. The primary motivations reported by interviewees for engaging citizens and stakeholders in a modelling process include reducing bias and filling data gaps, increasing the realism of and validating models, and building relationships, concerns which are also relevant to IAMs. There is a need to better understand the position of those who make decisions (e.g., who implement policies) but also the constraints (e.g., political feasibility, social acceptability, capacity of people to change) (P2).

5. Discussion and outlook

It remains unclear how to pursue integration because there is no clear answer. Our findings indicate that the current state of integration of social aspects in IAMs is limited for reasons including the lack of capacity of modellers, many of whom are already working to expand other important aspects of IAMs; lack of information, particularly quantitative data; and lack of resources and research objectives to justify their mobilization. Furthermore, opportunities to better include social aspects within large-scale modelling processes vary. Nevertheless, our findings offer some possible ways forward (**Table 2.2)**. We expand on these in the text below along with practical examples to help illustrate our recommendations.

Table 2.2. Challenges to integration and ways forward

Challenges	Ways forward
Lack of capacity of modellers (integration not always a priority)	• Increase enthusiasm and engagement for integration outside the modelling community to create buy-in and incentivize new approaches • Increase funding calls for integrative projects to solidify the importance of integration in research agendas and future workstreams
Lack of information (quantitative and qualitative data)	• Identify complementary research methods (e.g., systematic methods) for addressing data gaps • Engage with external actors (i.e., stakeholders) to inform models assumptions
Lack of resources for integration (merging not always feasible)	• Use situated modelling exercises to help determine what level of integration (and resource input) is truly needed to answer a research question • Adapt existing models (e.g., IAMs) in parallel to developing new ones

5.1 Demonstrate support to advance integration

As illustrated in the findings, the limitations of IAMs are widely acknowledged by IAM researchers in the literature. As also mentioned, however, the IAM community is working on challenging and relevant research questions that look at the aggregate, global system and often can already be addressed with the tools available. While it is important for IAMs to move towards being able to answer disaggregated questions about social processes, as these are essential to understanding implications of NbS, the onus cannot just be on the IAM community to catalyze this shift. One the one hand, funders play a role in soliciting answers to research questions that emphasize integrative work and inclusion of social aspects. On the other hand, the broader community of researchers (e.g., social scientists, complexity scientists, ecologists) working on NbS topics can also provide an impetus for the IAM community by introducing different ways of thinking and creating demand for integrated research.

One way these disciplinary silos are being bridged in practice is through working groups and consortia where researchers have shared objectives. If a project was interested in the impact of conservation policies on a region, for example, in one stream modellers could run different policy scenarios using a large-scale land use model, while in another social scientists could interview actors on the ground about their experiences, perspectives, and activities on the land. The project setting could then provide a bridge for researchers from both workstreams to come together and share results, ideas, and feedback. In some cases, qualitative results can be taken up in the computational modelling exercises, such as by informing constraints, potentially leading to a more iterative integration strategy. Even if results cannot be incorporated, the interdisciplinary discussions and learning are still beneficial for researchers to inform future research ideas, assumptions, and interpretations. Assessment processes such as the IPCC and IPBES demonstrate this on a global scale. Some groups are even going beyond bridging with a merged approach, such as the Large-Scale Behavioural Models of Land Use Change working group of the Global Land Programme (GLP). The interdisciplinary group aims to "support the creation of the next generation of large-scale, land-use change models that take account of human behaviour, agency and decision-making processes" (GLP, n.d.).

5.2 Look outside the models for new information

Complementary methods can be used to close remaining questions not answered by IAMs due to a lack of data. For example, one of the most comprehensive and widely known frameworks for systematically analyzing socio-ecological systems is the socio-ecological systems framework (SESF) (Ostrom, 2007, 2009). The framework initially emerged as a tool to assess situations of self-governance and collective action, but is increasingly being applied to questions of sustainability more broadly (Partelow, 2018). Applying this to an NbS context, Budiharta et al. (2016) propose an analytical framework for operationalizing a restoration planning approach that accounts for local and contextual dynamics using Elinor Ostrom's social-ecological systems framework and systematic decision-making.

Systematic evidence synthesis methods can also help to address concerns about the reliability of qualitative data. In the field of energy social science, for example, efforts are being made to produce quality computational text analyses (Müller-Hansen et al., 2020). In addition, there are examples of systematic approaches being used to evaluate the effectiveness of NbS and identify stakeholders (Chausson et al., 2020; Zingraff-Hamed et al., 2020), but more research is needed in this area to explore how they can better contribute to IAM processes. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), a high-level assessment body, has also made interesting steps in moving forward thinking on values and vested interests in society and for nature, and how to better identify and address them (Díaz et al., 2019). They developed a framework consisting of 18 cross-cutting categories to report on nature's contributions to people (NCPs). This has allowed them to move beyond epistemological differences and bring together diverse types of evidence.

Additionally, external actors are increasingly being consulted to inform model assumptions. Hänsel et al. (2020) use expert views to identify discount rates for economically 'optimal' climate policy paths, which historically have been disagreed upon. Cook-Patton et al. (2020) also approach experts after modelling restoration potential to determine feasibility of different opportunities. Palazzo et al. (2017) worked with regional stakeholders to develop narratives, scenarios, and assumptions about the future of agriculture and food security under climate change in West Africa. They then quantified these scenarios using the large-scale, global models GLOBIOM and IMPACT. The RESTORE+ project, which is developing scenarios for restoration and sustainable land utilization in Brazil and Indonesia, has similarly been following an iterative approach to integration. Regular meetings with stakeholders were held over multiple years to develop research ideas, present results, and support policy planning. Furthermore, because NbS are highly context dependent, co-creation and buy-in from stakeholders can be important (Giordano et al., 2020; Zingraff-Hamed et al., 2020). Engagement of stakeholder requires time, but it can enable a more efficient research process as efforts can be focused on more targeted research that is actually needed and wanted by people using the research.

5.3 Be strategic about integration strategies and objectives

While modellers likely know that a merged approach to integration is needed to fully answer their research questions, this is not always pursued. In many cases, iteration may be a more feasible and productive integration approach than trying to create a hard link. van Vuuren et al. (2016) argue that in practice, collaboration, rather than a true linking of disciplines, may be the outcome of integration. For example, this could mean working in an inter- and transdisciplinary way to develop research questions and a conceptual idea of an ideal model to decide what model or approach is appropriate to provide information about these questions. By situating the modelling exercise and asking, among a diverse group of experts and stakeholders, why it is taking place in the first place, researchers can assess what kind of integration within the model construct is needed. Future research on this topic could even explore opportunities for collaboration within a formal "situated modelling" framework, an emerging anthropological concept that seeks to go beyond integration and preserve productive tensions between disciplines (Niewöhner, 2021). Such a framework could be useful for identifying the limitations of computational models and information gaps that could be addressed through research using complementary methods.

There is also value to working to improve existing models, which have been thoughtfully developed by scientists over decades. Integration strategies following a merged approach may determine that existing IAMs are not appropriate for the research question, instead choosing to pursue a different type of model; alternatively, the focus may be on integrating segments of an IAM. In some cases, the latter may be worth pursuing, rather than creating a completely new model from scratch. IAMs are already providing crucial policy insights and understanding of technological and economic concerns given societally stated preferences like a temperature target (Jewell, 2019). This does not mean that new model development should not also be pursued. Rather, the contribution of IAMs should not be discounted and both approaches should be pursued in parallel.

In conclusion, we find that there is a need to incorporate social aspects in IAMs, but how this happens in practice depends on a number of factors. In the end, the choice, type, extent to which integration occurs may depend on context, project objectives, or pragmatic choices rather than conceptual notions about what 'good' integration is. At the same time, some integration strategies are better than others, and concerns about data limitations and low capacity of the IAM community for engaging in integration can be overcome with sufficient support and complementary efforts from the broader research community. Future research should continue to explore how integration is operationalized

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IV.3 Valuing the hidden benefits of forest-based climate change mitigation

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Abstract

Forest conservation and restoration continue to be undervalued, underpriced, and underfunded. Financing for forests mostly focuses on climate change mitigation, valuing forests for their carbon storage capacity. With increasing attention on the importance of biodiversity, ecosystem services, and preservation of indigenous and local cultures, however, it has become clear that there are visible and invisible co-benefits of forests that are equally – if not more – significant than carbon alone. As such, we review evidence supporting an expanded valuation of forests, and assess practical examples to overcome this valuation gap. We do this by first offering an economic framework for our analysis, defining a *social cost of deforestation* (*SCD*). We then use this lens to assess a suite of opportunities to appropriately value and monetize forest co-benefits. These identified tools may help avoid suboptimal outcomes arising from a carbon-centric approach – supporting policy discussions, and unlocking expanded public and private finance for forests.

Keywords

forests, nature-based solutions, climate change mitigation, co-benefits, ancillary benefits, theoretical framework, monetization, ecosystem services, ecosystem valuation, total value capture

1. Introduction

Forests provide enormous ecological, economic, and social value (Fuss et al., 2021; Golub et al., 2018; Kappen et al., 2020). The contributions of forests to society include climate change mitigation, biodiversity protection, provision of ecosystem services, preservation of indigenous culture, and human health impacts (Watson et al., 2018). One estimate puts the total economic value of forests between US$50 and $150 trillion, with the upper limit being nearly double the value of global stock markets (Kappen et al., 2020). In addition, forests hold immeasurable intrinsic value for nature and humanity (Dasgupta, 2021). They are an immense natural asset that is essential to the balance of our earth and human systems.

The climate benefits of forests have received growing attention over the last decade, in both scientific and policy spaces. Forest-based carbon mitigation could play a particularly important role in stabilizing and reducing CO2 concentrations while the world transitions away from fossil fuels (Harris et al., 2021; Houghton & Nassikas, 2018). Recent studies support the notion that reforestation, avoided deforestation, and improved sustainable forest management are crucial strategic tools to prevent and reverse the worst long-term impacts of climate change (IPCC, 2019). These mitigation pathways are also the most readily available for implementation (Girardin et al., 2021); in particular, forest conservation offers a large percentage of potential mitigation among natural climate solutions (NCS) and is also among the most cost-effective of NCS abatement pathways (Roe et al., 2019). For these reasons, the climate benefits of forests have received growing attention over the last decade, in both scientific and policy spaces.

Incorporating these benefits into market-based decision making and policy priorities, however, can present a challenge. This is perhaps due to the time lag of these potential climate benefits from the moment of avoided deforestation, when pitted against conflicting priorities with more immediate and concentrated impacts (Lohmann, 2001). Yet these long-term climate benefits are not the only value that forest systems provide. The forest-based climate change mitigation pathways noted above provide biophysical, socioeconomic, and other co-benefits spanning biodiversity, human health, green infrastructure, improved governance, and other benefits yet to be fully articulated (Soto-Navarro et al., 2020). These co-benefits of forest-based climate actions provide a host of more immediate welfare effects, which provide significant additional incentives for decision-makers to deploy them (Ürge-Vorsatz et al., 2014).

Despite these diverse and enormous benefits, preserving global forests is proving to be one of the greatest challenges of our time, as the international community continues to unsustainably deplete their collective natural assets (Dasgupta, 2021). According to estimates from the Food and Agriculture Organization of the United Nations (FAO), over the last decade the world lost 13 million hectares per year – an area the size of Greece (FAO, 2020). This trend has mostly been driven by actors clearing land to support the expanded production of agricultural commodities (Curtis et al., 2018; Pendrill et al., 2022). In addition to the land use change driven by the conversion of forest areas for commercial purposes, significant forest degradation and value loss has also been driven by changing climatic factors such as drought, wildfires, and pests – factors which may have synergistic effects that worsen one another as further land conversion and climate change progress (Réjou-Méchain et al., 2021). On the current trajectory, one third of total forest value may be lost by 2050 (Kappen et al., 2020).

In response to these unsustainable deforestation and degradation trends, prominent global coalitions are working to mainstream recognition of the value of forests and halt their destruction. The Bonn Challenge, for example, aims to restore 350 million hectares of degraded and deforested landscapes by 2030. The New York Declaration of Forests (NYDF) sets out ten goals contributing to global forest conservation, such as livelihood support to local communities and improved forest governance. In addition, countries have voluntarily committed to restore over 230 million hectares of degraded forests in the next decade through Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change (UNFCCC) (Fagan et al., 2020). More recently, at the UNFCCC Conference of Parties in Glasgow (COP26), 141 countries representing over 90 percent of the world's forests committed to collectively halt and reverse forest loss and land degradation. These initiatives highlight awareness of multiple benefits of forests beyond carbon storage and sequestration[7], and that countries agree that curbing climate change must simultaneously promote the rights of indigenous peoples, gender equality, health, human rights, and more. This is also reflected through the Sustainable Development Goals (SDGs), which include multiple targets that forests contribute to such as addressing hunger, reducing poverty, and providing freshwater.

Despite the growing international recognition of the relevance of forest co-benefits for society, they remain undervalued, underpriced, and underfunded. The nature funding gap is estimated to be between US$598 and US$824 billion, meaning we need to be spending at least that much more to reverse decline in biodiversity (Deutz et al., 2020). As Costanza et al. (1997) put it, "because ecosystem services are not fully 'captured' in commercial markets or adequately quantified in terms comparable with economic services and manufactured capital, they are often given too little weight

[7] The importance of forests to carbon storage and sequestration has also been formalized by the UNFCCC, first through the Clean Development Mechanism (CDM) under the Kyoto Protocol and later through the mechanism for Reducing Emissions from Deforestation and Forest Degradation (REDD+) under the Paris Agreement. The former made afforestation and reforestation projects in developing countries eligible for financing from developed countries because of their mitigation services, while the latter incentives countries to protect their forests through readiness and results-based payment programs.

in policy decisions". Few widely accepted or implemented frameworks exist to account for them in policies and markets. The *social cost of carbon* (*SCC*), for example, omits economic impacts related to the loss of ecosystem services, essentially valuing them at zero (Druckenmiller, 2022). Meaningfully estimating the value of forest benefits can be technically and politically challenging; there are different ways to measure value, and forests hold different value for different actors (e.g., Cáceres et al., 2015). Moreover, attempting to articulate the value of forests in monetary terms can be contentious. Some critics, for example, argue that economic valuation is a distraction from a warranted focus on ending destructive and exploitative projects (Unmüßig, 2016).

In addition, the literature to date on the co-benefits of forest-based climate change mitigation activities is limited. Most such studies examine the services provided by certain forestry activities or forest types (Calvo-Rodriguez et al., 2017; Himes-Cornell et al., 2018). A global meta-analysis by Mengist & Soromessa (2019) found that co-benefits research has focused on provisioning, regulating and cultural ecosystem services, such as timber production, water supply, carbon sequestration, and recreation. Yet, while ecosystem services are essential to supporting biodiversity, research on ecosystem services does not typically include biodiversity indicators.
Nevertheless, understanding the co-benefits of avoided deforestation is an essential foundation for mobilizing new investment to protect forests and the enormous value they provide (Sarira et al., 2022). They also provide an entry point for leveraging collateral investment (i.e., investment from secondary sources) for forests. Economic or social benefits shape the motivation of profit-seeking investors, public institutions, philanthropists, and impact investors to contribute funds in forest protection. The emerging carbon market, for example, highlights carbon as a primary benefit, yet buyers are increasingly focused on performance metrics beyond carbon (Goldstein, 2016). Similarly, climate finance donors, such as the Green Climate Fund, are increasingly requiring proposals to identify co-benefits. Clearer frameworks to discuss and define this valuation of forest co-benefits, and the link to social and economic outcomes, could help ease the adoption of the policies and market practices needed to bring these co-benefits the attention (social and financial) they warrant.

To advance this need, we explore how we can better reflect and communicate the full value of forest benefits in policy discussions. Specifically, we (1) bring together different concepts and provide a theoretical framework for analysis of the potential economic damages due to the loss of both forest carbon benefits and co-benefits, which we call the *social cost of deforestation* (*SCD*); (2) explore valuation of forest co-benefits in practice, focusing on high-level assessments and carbon crediting frameworks; and (3) propose some concrete ways forward that can be useful for policymakers and governments. Though we draw primarily from examples and our experiences working on tropical forests, the insights and lessons from this paper are also relevant to valuing other types of forests and ecosystems.

2. Theoretical Framework

Defining forest co-benefits

We understand forest co-benefits as all the benefits to society provided by forest-based climate change mitigation. In most cases, these are additional benefits occurring in climate-positive activities where a primary aim is carbon sequestration. We take carbon and climate policies as our starting point because the implementation of forest activities are still occurring within a strongly carbon-centric framework, such as the REDD+ mechanism[8] and voluntary carbon market. At the same time, the emergence of co-benefits has occurred in the context of increased consensus around the need for forest carbon offsets to also provide other social and environmental benefits. Even among REDD+ stakeholders, however, there are three competing normative perspectives: carbon-centric (the primary aim should be carbon sequestration); carbon-centric with an emphasis on safeguards (the current approach adopted by the UNFCCC); and co-benefits-centric (which puts both carbon and co-benefits as primary goals of REDD+) (Vijge et al., 2016).

While there is no universally accepted classification of forest co-benefits, several scholars and institutions propose typologies of what these benefits could entail in the context of forest-based climate change mitigation. Katerere et al. (2015) propose three broad categories: social (improved economic livelihoods), environmental (ecosystem services provision), and governance (improved forest governance) benefits. Similarly, Lee et al. (2011) posit that REDD+ co-benefits can be classified according to five goals: conserving biodiversity, protecting ecosystem services, community benefits, economic benefits, and adaptation needs. While these two typologies overlap in terms of environmental benefits, Lee et al. (2011) include adaptation needs and differentiate between economic and community benefits. They refer to economic benefit as the potential income stream that countries receive for REDD+ implementation, while community benefit refers to the direct livelihood improvement of local people and communities on the ground, where projects are implemented. Another third typology emphasizes the institutional benefits of REDD+, specifically the indirect improvement of governance (land tenure, law enforcement) and institutional capacities (Luttrell et al., 2018).

Relating valuation to monetization

Values refer to "norms that allow judging, individually or collectively, if something is good, beautiful, true, useful, moral, etc." (Salles, 2011). Valuation, the process of assigning value to goods, requires the development of frameworks for understanding how a potentially valued good should be judged against these norms. Valuation frameworks can serve as tools for rational decision making related to resource use, conservation, and the opportunity costs of one action over another. Economic valuation, and the decision frameworks that flow from it, usually have an

[8] Reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries

anthropocentric focus – they are ultimately based on the impacts of choices and actions on human well-being, defined across various measures and scales.

Economic valuation is closely tied to monetization, as economic values are often expressed in monetary terms. Monetization is the estimation or conversion of the value of a good *into terms of units of currency* (Silvertown, 2015). Distinct from setting prices on a good, the process of monetization can allow the inclusion of benefits and costs in decision making frameworks that otherwise might be unable to capture them for consideration and comparison, especially frameworks considering large financial flows. Monetization can make intangible benefits more concrete for the purposes of such comparisons– in a sense, making the invisible visible on a balance sheet. But monetization, and the extent to which a monetized estimate reflects the 'true' total value of a good, is deeply shaped both by the depth of our understanding of the relevant benefits of the good in question, and by our ability to meaningfully convert these benefit streams to financial terms, through a diverse range of possible approaches.

Cost-benefit analysis has been increasingly adopted as a common framework for valuation over the last decades. Today, it often serves as a major basis for decision making within corporate finance and public policy, across many sectors and geographies. The popularity of this method may be rooted in its apparent simplicity – adding up estimates of a list of costs and benefits and then comparing. But particularly in the context of environmental decision and policy, where the benefits of a good or action may be intangible and distant compared to immediate near-term financial costs incurred by a decision-making actor, this framework can pose serious challenges. Effective cost-benefit analysis depends on comparable units of valuation; monetization is potentially useful to help bring otherwise intangible benefits into comparable units of a common currency. However, if the full value of certain environmental goods are not yet even fully understood and articulated, they cannot be adequately quantified for comparison, much less meaningfully and fairly monetized. In line with this concern, critics of the monetization of nature argue that doing so also reduces its intrinsic value (that is, perceived value in its own right) down to the insufficient monetary value.

Finally, as true market prices stem from an equilibrium between supply and demand, they are rooted in both a collective 'willingness to pay' for a scarce good – and in a collective *ability* to pay, which may or may not fully align with need or desire. Willingness to pay is also shaped by the information that a potential buyer has about a good, and what of that is salient to their decision-making processes. For example, an actor weighing a business decision to clear a forest and sell the timber may not be aware of the benefits of this forest to her local water supply and quality; she might value the forest more highly if she knew this– or, more importantly, if she understood the implications of the loss of these benefits for the future of her downstream aquaculture operation.

Understanding the *social cost of deforestation*

Carbon benefits, by default, currently play the role of the primary benefit justifying the core investment in forest preservation. Additional benefits justify the collateral investment, such as the positive return of transition from extensive to intensive cattle ranching (Golub et al., 2021). Over time, however, the value of individual benefits, or components, that constitute the total value of a forest may change. This can happen through various processes of land-use change, the most drastic being deforestation. As such, we introduce a new framework for capturing this change in value, which we call the *social cost of deforestatio*n.

Since the publication of a seminal article by Pearce (1990), economists have used the concept of the *total economic value* (*TEV*) of the forest to map use and non-use value derived from a range of forest co-benefits. We argue that there is rationale for a leap from just the economic value of forests to the social value of forests, which we understand as the *social cost of deforestation* as it represents the potential economic damage from the loss of both carbon and other co-benefits (**Figure 3.1**). Similar to the *social cost of carbon*, which is defined as "the monetary value of the damage done by emitting one more ton of carbon at some point of time" (Pearce, 2003), the *SCD* reflects the net present value of the lost benefits from deforested land (damage). The *SCD* concept, however, is broader than the *SCC*. The *SCC* usually considers global damage, without concern for where the additional ton of CO2 was emitted. With the *SCD*, on the contrary, location plays an essential role in defining the value, which is a combination of global and site-specific losses.

Specifically, the *SCD* can be presented as a sum of three major components:

- Monetized benefits;
- Monetizable benefits; and
- Non-monetizable benefits that have a social value quantifiable in economic indicators

Monetized benefits reflect current revenue from ecosystem services provided by forests. These benefits create an economic barrier to deforestation that competes with other land use options that require deforestation. Examples of revenue streams created as long as the forest is preserved include sales of nontimber products, revenues from initial REDD+ intervention, philanthropic contributions, and conservation support from the government.

Monetizable benefits (but not yet monetized) include future revenues from trading high quality, high integrity emission reductions – which are likely to incentivize conservation and produce co-benefits on a large scale – for a fair market price. These include external benefits such as soil erosion prevention and watershed protection. These benefits could be monetized as a result of specific interventions targeting some or all of them.

Non-monetizable benefits may still have economic value but not be monetizable in terms of increased revenue or output. For example, health risk reduction, say, avoided mortality has a high economic value calculated as the value of statistical life but a positive economic impact on output due to preventing loss of labor is negligibly small relative to the economic value of social benefits of avoided mortality. Some benefits are intangible but should be taken into account even if their economic value cannot be calculated.

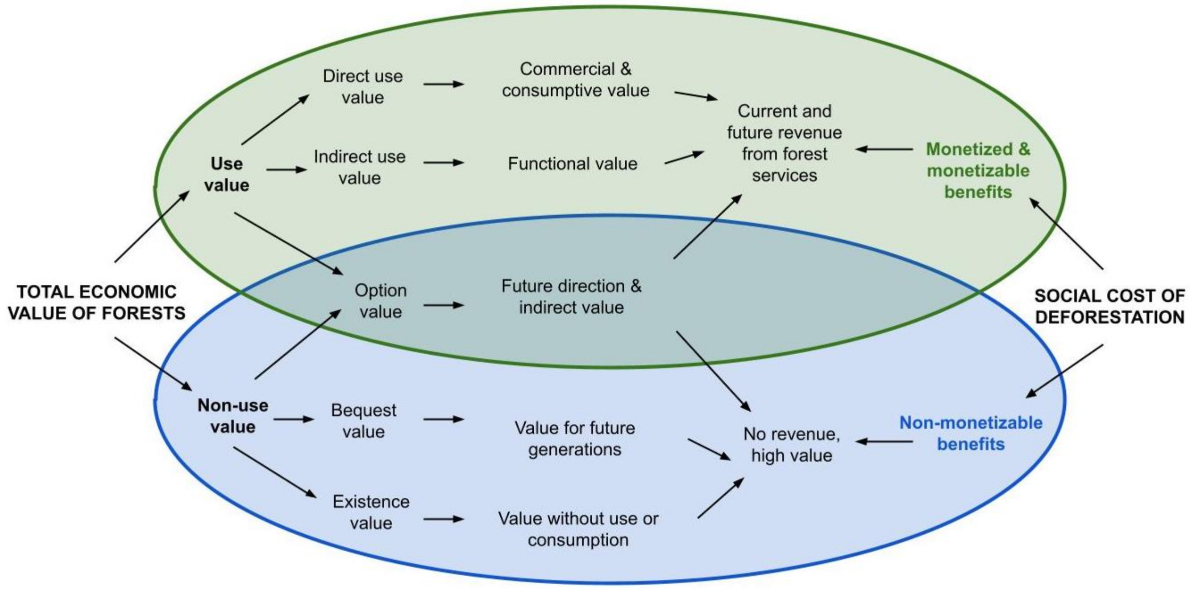

Figure 3.1. Expanding the TEV concept with the SCD concept. *Total economic value* separates most forest value into use or non-use values (adapted from Pearce et al., 2020). The *social cost of deforestation* provides a bridge to conceptualize the changes in forest value, and importantly, future potential value.

Because of the irreversibility of deforestation, taking a forward-looking analysis of benefits is essential. This allows for two complementary processes to be accounted for:

- Change in time value of different components of *TEV* of in more general terms *SCD*;
- Catchup of *TEV* with *SCD*

The literature on the Environmental Kuznets Curve (EKC) can help us to understand how these processes occur. The hypothesis of the EKC argues that an increase in per capita income first coincides with an increase in pollution but when per capita consumption reaches a certain critical level, pollution becomes a decreasing in per capita consumption function (Dinda, 2004). In other words, it postulates an inverted-U-shaped pollution dynamic – in our case the utility of deforestation – as a function of per capita income. As such, the changes in the value of *SCD* components are driven by transformations in the utility function of deforestation as the economic context evolves and transformations in the global and local ecosystems occur (**Figure 3.2**). For example, transformation of the utility function may lead to an increase in the relative value of the forest as a whole and changes in the relative value of individual components of ecosystem services. Different transformations take place on the global, national, and local levels.

As such, understanding local dimensions of co-benefits are essential to predict the reliability of local institutions in enforcing of forest conservation (including avoided deforestation, reforestation, and prevention of forest degradation) and realistic assessment of local participation. For example, when communities have a strong understanding of the multiple benefits of forests, and policy aligns with their values, they are more likely to comply with conservation policy and keep politicians accountable for enforcement of conservation programs and policies (Nurrochmat et al., 2019). This also suggests that region-specific *SCD* may be a good communication tool to encourage local authorities to contribute to forest preservation, as locally tailored *SCD*s can help regional institutions and decision makers understand the value of protecting their own forests.

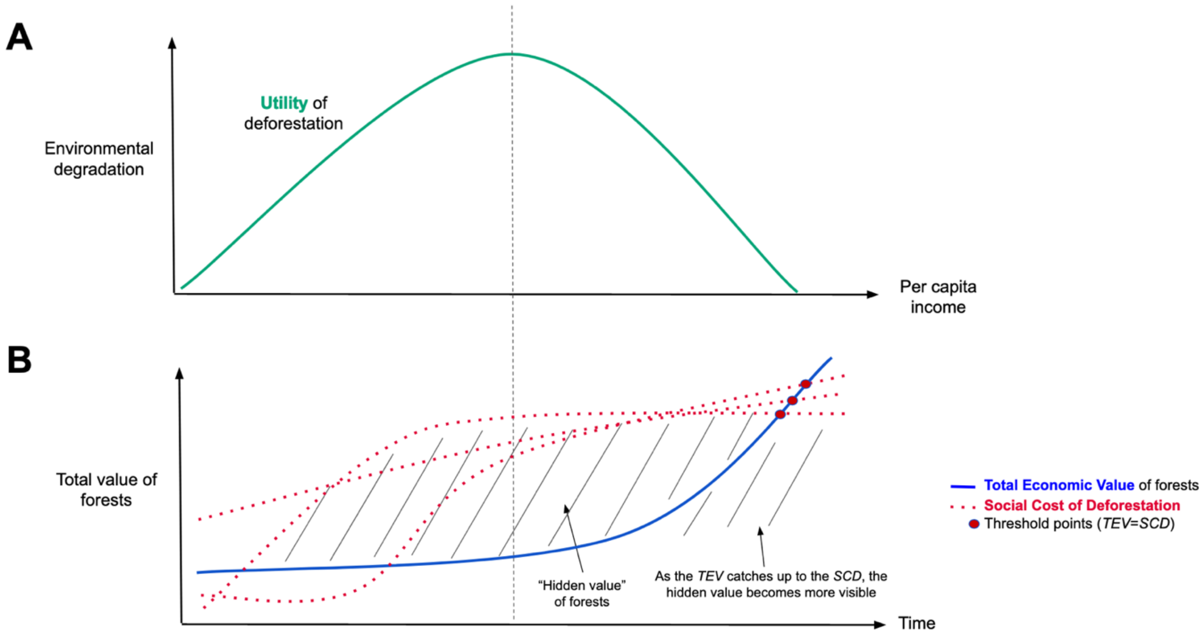

Figure 3.2. Illustrating the SCD alongside the Environmental Kuznets Curve framework. As deforestation increases (A), the *social cost of deforestation* increases because each unit of damage from deforestation comes at a greater cost to society (B); once deforestation peaks the *SCD* remains high because the value of forests has been recognized by society. As the gap between the *total economic value* and *SCD* narrows, hidden value of forests becomes visible. The red lines illustrate potential trajectories for the *SCD*, though the possibilities are not limited to these three options; in reality, the trajectory of the *SCD* will depend on contextual conditions.

Furthermore, only a fraction of *SCD* values is monetizable or monetized, but this fraction changes over time. The social value of carbon changes over time, as does the value of biodiversity and other ecosystem services. The remaining values represent the non-monetizable benefits, in which case it may not always be necessary to assign a specific value to the benefit, but there could still be a cost associated with it. For example, with irreversible changes to the forest system such as the extinction of a species, the cost could be infinity if that species plays an important role in maintaining ecosystem functioning.

In addition, the share of different components (non-monetized benefits, monetizable benefits, and monetized benefits) of the *SCD* also changes. For instance, the proportion of intangible (i.e., non-monetizable) goods included in the *SCD* is currently high. Due to changes in preferences and in response to increased scarcity of forested land, the *SCD* is likely to increase in time: advances in climate policy and building institutions to protect forests will likely increase the share of monetizable benefits; advances in the economic valuation of ecosystem services and increased demand for ecosystem services will likely also increase the share of monetizable benefits, revealing the "hidden value" of the forest. This transformation of the *SCD* and changing share of its components are illustrated in **Figure 3.3**.

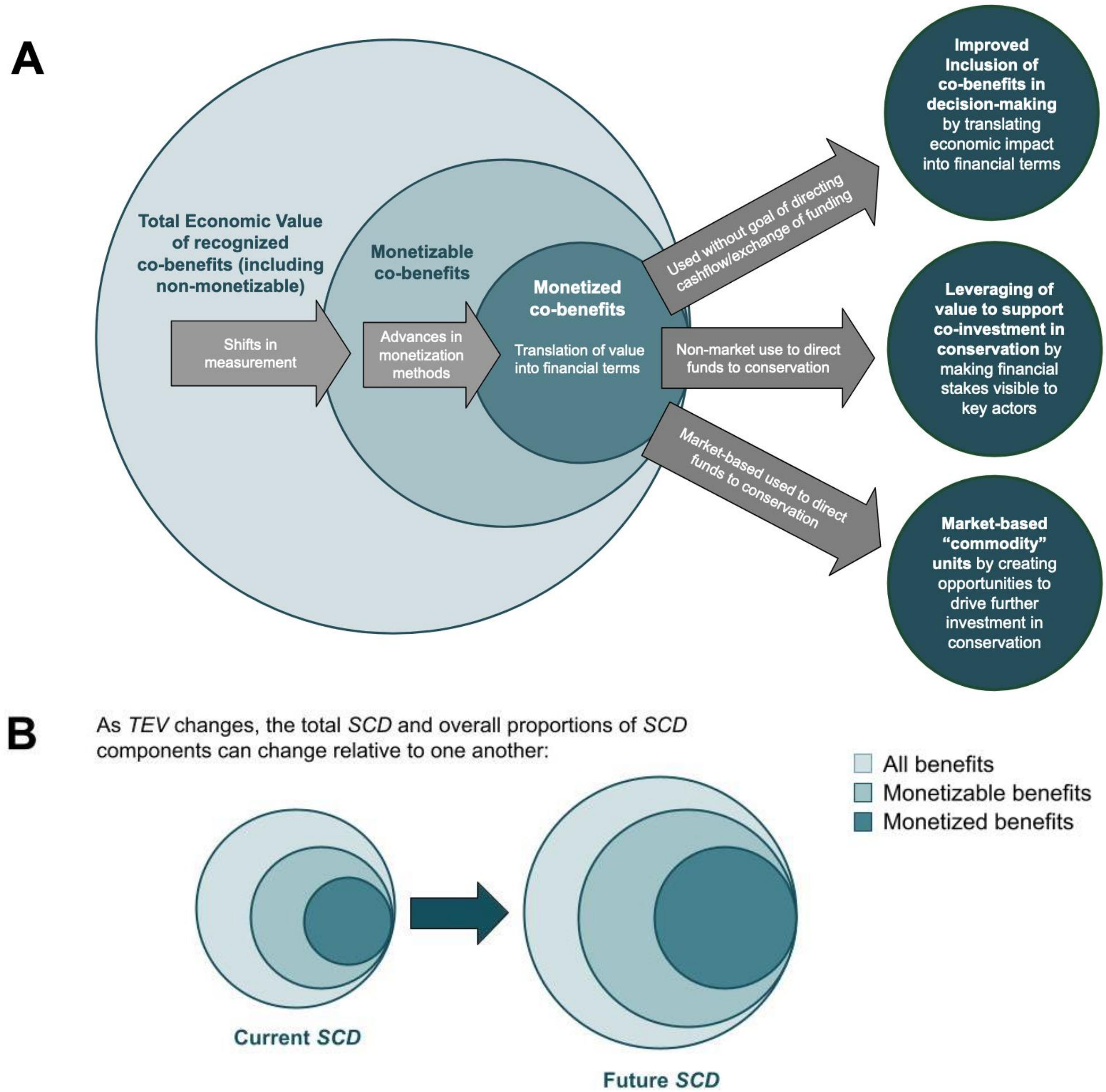

Figure 3.3. Transformation of SCD components. (A) Shifts in measurement create opportunity for forest value to be recognized as monetizable, some of which becomes monetized, or made visible in financial terms; (B) over time, overall *SCD* can change (e.g., increase) as can the individual components.

In the future, some previously unknown benefits of forests may also be revealed. This could happen if a new function or social value of forests is discovered. In this case, the process of transformation of *SCD* and its components might be more complicated. For example, imagine you have a national forest with protected upstream water resources. The total value of the resources in the forest are much larger than any economic benefit. As soon as authorities collect a fee from visitors, a fraction of the monetizable benefits becomes monetized. If authorities introduce water charges downstream, then another fraction of monetizable benefits is monetized. If, however, there is currently no monetization all external benefits are in theory, monetizable. As more benefits are socially recognized or discovered, the opportunities for monetization become endless, but this does not mean monetization will occur. In this sense, it is also possible that the gap between total value and monetizable value may never fully close and the non-monetized benefits remain; we elaborate on strategies for capturing the non-monetizable value in the **Outlook** section.

3. Valuing forest co-benefits in practice

Representation in high-level assessments

Over the last two decades at least four leading scientific initiatives have attempted to compile and consolidate scientific knowledge on how ecosystems, forests, and biodiversity are valued globally (**Table 3.1**). Under the umbrella of the United Nations, the Millennium Ecosystem Assessment (MEA), the Economics of Ecosystems and Biodiversity (TEEB), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) all outline ways to estimate the value of nature. Similarly, the World Bank has been conducting annual assessments of natural capital accounting with their Changing Wealth of Nations (CWON) reports. These assessments are supported by international platforms for science and policy, which have potential to influence the development and trajectory of forest conservation investment globally.

Table 3.1. High-level assessments reviewed

Initiative/ Assessment	Last report	Relevance	Insights/method for valuation
Millennium Ecosystem Assessment (MEA)	2005	First international initiative measuring the value of ecosystem services for human wellbeing	• Argues Market approaches can only be used to estimate the value of few forest services, mostly the ones related to provisioning services and that enter formal markets • Acknowledges that there is no consistent methodology, and usually insufficient and incompatible information, to estimate credible values for many other forest services, such as habitats for biodiversity • Acknowledges that researchers have successfully applied monetary methods to "non-market" and often "non-traditional" services • Identifies *Total Economic Value* as the most widely used framework for identifying and categorizing forest benefits

The Economics of Ecosystems and Biodiversity (TEEB)	2008	Highlighted growing costs of biodiversity loss and ecosystem degradation; a motive of the study was to establish an objective global standard basis for natural capital accounting	• Proposed a three-step method for valuing poorly or undervalued ecosystem services
			  • Identify and assess the full range of co-benefits to be valued (recognize them)
			  • Estimate and demonstrate their value
			  • Capture value and seek solutions to overcome under-valuation, using economically informed policy instruments

Changing Wealth of Nations (CWON)/ The System of Environmental Economic Accounting (SEEA)	2021	CWON uses the SEEA, which is the official international framework for natural capital accounting; SEEA Ecosystem Accounting (EA) is the first internationally agreed-upon statistical framework for ecosystem accounting	• A framework of five core accounts makes up the building blocks of the SEEA EA: Ecosystem extent, ecosystem condition, ecosystem services, ecosystem monetary asset and thematic accounts • Accounts constitute an accounting system which presents a comprehensive and coherent view of ecosystems • To value forests, the CWON report uses international forest statistics from FAO and its metric is U$S

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)	2022	Introduced the concept of *nature's contribution to people*, which embraces a wide range of descriptions of human-nature interactions, including the concept of ecosystem services and other descriptions, ranging from utilitarian to relational	• Offers a systematic assessment of over 50 different methods found in the literature for valuing nature
			• Groups methods into four non-disciplinary 'method families'
			  • Nature-based valuation gathers, measures or analyses information about the properties of nature and its contributions to people
			  • Statement-based valuation directly asks people to express their values
			  • Behavior-based valuation identifies how people value nature by observing their behavior and practices
			  • Integrated valuation brings together various types of values assessed with different information sources

The MEA was the first to highlight the challenges of estimating credible values for many forest services (MEA, 2005). The TEEB dedicates a full chapter to forests and proposes payments for ecosystem services (PES) and REDD+ as measures to correct failures of markets to value biodiversity and ecosystems (TEEB, 2008). The CWON measures natural and human capital in the form of assets (World Bank, 2021). Similar to the MEA, critical services such as biodiversity habitat and species protection, cultural and/or existence values, or landscape aesthetics are not included in the CWON due to the lack of proper market equivalent values consistent with the wealth accounting methodologies. Carbon retention is another key ecosystem service not considered. Differently to MEA, IPBES recently introduced the concept of *nature's contribution to people*, which was developed to embrace a fuller and more symmetric consideration of diverse stakeholders and worldviews, and a richer evidence base for action (Díaz et al., 2018). The reporting system for *nature's contributions to people* has a gradient of complementary and overlapping approaches, ranging from a generalizing to a context-specific perspective.

These above-mentioned assessments have been picked up extensively by the mass media, reaching a broad audience and shaping global narratives. Furthermore, they have served as the theoretical foundation of environmental damage proceedings brought before the International Court of Justice (ICJ). In February 2018, for example, after Nicaragua excavated a channel on disputed territory, the ICJ ordered it to compensate Costa Rica for damage to its rainforests and protected wetlands (I.C.J., 2018). The case is significant for at least two reasons: it was the first time the ICJ decided on an environmental damage case; and the ICJ's decision explicitly recognizes that the environmental damage includes ecosystem services. The ICJ accepted Costa Rica's claim that biological diversity and ecosystem services merit valuation, and partially grounded its decision by referring to the different categories of ecosystem services developed in the MEA. In short, there was a science base that supported its claims. In the immediate future, as climate and environmental litigation continues to develop, the need for better mechanisms to value nature will become increasingly prevalent. With climate litigation cases growing exponentially in recent years, this will become increasingly important (Setzer & Higham, 2022).

Inclusion in crediting standards

A study on the emerging market of forest co-benefits found that they are often the major reason why buyers engage in forest carbon markets in the first place (Goldstein, 2016). These positive co-benefits — in particular biodiversity and community impacts — are even of equal or greater importance to some buyers of emissions reductions than the carbon credits themselves. It remains, however, difficult to track the impacts of carbon projects beyond carbon as these are not often included in assessments. This is in part because individual impacts are very context-specific, and measuring them could mean additional transaction costs for projects. At the same time, there are also potential negative impacts, or trade-offs, that may occur in the implementation of carbon projects. As such, to evaluate forest co-benefits in carbon standards we must consider on the one hand, what criteria and indicators are in place to ensure positive co-benefits are accounted for in project design; and on the other hand, what environmental and social safeguards are in place to minimize adverse outcomes.

We use the forest carbon standards reported on by Ecosystem Marketplace, an initiative publishing information and reports on financing for ecosystem services, as our starting point. Specifically, we review four of the most commonly used standards for certifying forest projects in the voluntary carbon market (VCM): the Verified Carbon Standard (VCS), the Gold Standard, Plan Vivo, and the Climate Action Reserve (CAR). We also look at the newer The REDD+ Environmental Excellence Standard (TREES), which aims to provide a market pathway for high integrity emission reduction and removals credits coming from countries and sub-national jurisdictions.

Currently, most activity related to forest credits takes place in the voluntary carbon market as most compliance markets, such as the European Union Emission Trading System, have limited inclusion or exclude forests from their crediting schemes (Maguire et al., 2021). Lessons from the VCM, however, may still be applicable to compliance markets as they are expected to grow in the near future. This is indicated by recent negotiations under Article 6 of the Paris Agreement, which deemed REDD+ credits eligible for international transactions as long as they comply with the rules and meet quality criteria (Streck, 2021). The emergence of new compliance mechanisms, like the United Nation's Carbon Offsetting and Reduction Scheme for International Aviation

(CORSIA) program, also hints at this as they plan to accept forestry and land-use offset standards (Maguire et al., 2021).

We find that the carbon standards we evaluated vary in their scope and coverage of forest activities (see **Table 3.2**; **Appendix**). Additionally, some capture co-benefits directly within their standard requirements, while others ensure environmental and social safeguards by partnering with complementary standards to certify co-benefits beyond carbon. The latter seems to be the case with the larger standards, like VCS and Gold Standard, while direct integration in the standard framework occurs with Plan Vivo and TREES, which both have a more specific mandate. Plan Vivo prioritizes smallholder projects, which are mostly land-based, while TREES focuses specifically on REDD+ transactions, with the aim to unlock long-term financing for forest protection and restoration.

However, there is still room for improvement. Forest projects remain a relatively small share of carbon credits, meaning the amount of certified co-benefits is likely even smaller. Furthermore, while some standards represent individual co-benefits well, few are comprehensive in their coverage of co-benefits. A report reviewing carbon market standards for REDD+ projects came to similar conclusions. No one standard scored at least 80% across all areas of their evaluation framework, which included 'climate integrity', 'biodiversity conservation' and 'human and community rights, stakeholder participation and sustainable community development' categories (Schmidt & Gerber, 2016).

Table 3.2. Forest carbon standards reviewed

Carbon standard*	Year established	Categories of forest use certified (as described by the carbon standard)	Co-benefit standards	Co-benefit considerations	Register-ed forest projects†	Forest projects as % of total†
Verified Carbon Standard (VCS)	2005	• Afforestation • Reforestation and revegetation (ARR) • Improved forest management (IFM) • Reduced emissions from deforestation and degradation (REDD)	• Climate, Community, and Biodiversity (CCB) program	• Must demonstrate contribution to at least three SDGs • Can certify with additional standards (e.g., CCB, SDVista) to recognize non-greenhouse gas (GHG) social and environmental benefits	225	11% (out of 2022 projects)
Gold Standard	2003 (Clean Development Mechanism) 2006 (voluntary market)	• Afforestation / Reforestation (A/R)	• Fairtrade Climate Standard	• Can certify additional SDG impacts (e.g., via SustainCERT) such as renewable energy certificate labels; water benefit certificates; gender equality impacts; improved health outcomes; black carbon reductions	32	2% (out of 1984 projects)

Plan Vivo	1994	• Protection (Reducing deforestation and/or degradation of forests) • Restoration (tree planting, assisted natural regeneration, and management to restore ecological function) • Improved management (Improving forest management practices to increase carbon stocks and/or reduce greenhouse gas emissions)	• No complement-ary co-benefit standard	• Requires "positive impacts on local livelihoods and ecosystems" • Requires a benefit-sharing mechanism (at least 60% of carbon sale must go to community or smallholder) • Requires setting of a livelihood and ecosystem baseline • Requires the provision of long-term livelihoods benefits that are additional to the sale of certificate of employment in projects	25	89% (out of 28 projects)
Climate Action Reserve (CAR)	2001 (began as California Climate Action Registry)	• Improved forest management • Avoided conversion (forestland to non-forest use)	• No complement-ary co-benefit standard	• Not reported on	115	61% (out of 188 projects)
The REDD+ Environmental Excellence Standard (TREES)	2021	• All Reduced emissions from deforestation and degradation (REDD+) activities except removals from forests remaining forest	• Announced a co-benefit certification under development in 2023	• Sets its environmental, social, and governance requirements in line with the Cancún Safeguards	17	100% (out of 17 projects)

* Information on standards sourced from documents on organization websites (ART, 2023c; CAR, 2023; Gold Standard, 2023; Plan Vivo, 2023; Verra, 2023)
† VCS, Gold Standard, Plan Vivo, and CAR data accessed January 11, 2023 on the Voluntary Carbon Market Dashboard (Climate Focus, 2023); TREES data accessed February 13, 2023 on the Architecture for REDD+ Transactions registry (ART, 2023a)

4. Outlook: Examples and opportunities

As discussed above, there is increasing global recognition of multiple streams of benefits from forest-based mitigation activities. But emerging valuation approaches in practice currently are diverse, and many assessments still do not consider the full potential of forests. Examining methods and frameworks currently in use for valuing co-benefits can help identify new opportunities to mobilize increasing funds for forest preservation. To this end, we discuss in this section some practical ideas that could be extended to capture a more complete valuation of forests in decision-making.

In the **Theoretical Framework** section, we defined total forest value as consisting of monetized benefits, potentially monetizable benefits, and non-monetizable benefits. Here, we first consider tools for shifting potentially monetizable benefits towards monetized, primarily by extending existing markets and finance tools. We then discuss non-market opportunities to leverage previously uncaptured value from non-monetizable benefits. Some of these approaches have implications for both market- and non-market-based mobilization of funds; we discuss the example of jurisdictional REDD+ to illustrate this (see **Box IV.2**).

Market-based strategies for capturing monetizable benefits

There is currently a high proportion of unmonetized benefits in the *SCD*. We discuss market-based strategies for leveraging these benefits that build on the success of carbon markets and of existing financing mechanisms for ecosystem services. We also consider opportunities for driving new investment using a *green alpha* methodology, a novel approach for estimating the hidden benefits of avoided deforestation and assessment of these benefits in monetary terms.

Further embed valuation of co-benefits into existing carbon markets

Interest in "high-quality" carbon credits is rising, particularly given increasing public scrutiny and media conversations highlighting the potential dangers of insufficiently rigorous forest carbon crediting frameworks (see, for example, discussion in Nasi & Pham, 2023). This demand is already beginning to translate into increased prices, and therefore increased potential for financial support of well-implemented REDD+ activities credited under high integrity frameworks; for example, a 2015 study found that voluntary credit purchasers, particularly nonprofit or government buyers, were willing to pay a significant price premium for Gold Standard credits, used within the study as a proxy for quality (Parnphumeesup and Kerr, 2015).

A 2016 study suggests that credits generated under standards with a co-benefits emphasis were more likely to be successfully sold to a buyer (Lee et al., 2016). Within the voluntary carbon market, this protection and enhancement of forest co-benefits within crediting standards also aligns with reported motivations for some classes of credit purchasers (Goldstein 2015). As illustrated in **Table 2**, many major forest-based emissions crediting standards already incorporate requirements for environmental and social safeguards that protect and maintain key forest co-benefits. Other standards are beginning to elevate formal recognition of these co-benefits; for example, Architecture for REDD+ Transactions (ART) has recently launched a process to develop a formal co-benefits certification option as part of its jurisdiction-scale TREES crediting framework (ART, 2023b).

This emerging trend could be further leveraged by promoting standards and rules privileging high-quality forest carbon standards – including those that protect and enhance forest co-benefits—within compliance markets and common voluntary emissions target-setting frameworks. In alignment with this, third-party efforts to define credit quality increasingly highlight the inclusion of environmental and social safeguards that align with the enhancement of ecosystem services and other co-benefits, particularly as they relate to impacts on indigenous and local stakeholders.

Recent and ongoing nonprofit efforts to define carbon credit quality include the Tropical Forest Crediting Integrity Guide (COICA et al., 2023), the Integrity Council for the Voluntary Carbon Market (ICVCM) Core Carbon Principles guidance and Assessment Framework development process (ICVCM 2023), and the Carbon Credit Quality Initiative (CCQI). Credit rating efforts from for-profit companies are also emerging as the value of traded credits continues to rise. To the extent co-benefits are included, whether explicitly or implicitly, such emerging frameworks for assessing the quality of forest-based credits generally associate credit generation efforts that enhance aspects of forest co-benefits with preferential ratings. Expanding the association of these co-benefits with definitions of higher carbon credit quality may in turn open the door for higher future prices and increasing flows of forest finance.

Target nature-related financial risks to leverage emerging finance mechanisms

Recent innovations in finance to support ecosystem services are beginning to unlock funds to incentivize forest conservation specifically on the basis of their monetized co-benefits. One illustrative example of relevant innovation in this space is the Cloud Forest Blue Energy Mechanism (CFBEM) (Narvaez et al., 2017). The CFBEM relies on the ability to model and monetize particular co-benefits of forest conservation and restoration, enabling beneficiaries to *"pay for success"* of direct financial benefits provided by the conservation and enhancement of forests. Specifically, a major co-benefit of restored and protected cloud forests is the prevention soil erosion; these benefits are in turn monetized based on their impact to the operating costs of hydropower companies (i.e., reductions in expenses related to reservoir sediment dredging, due to enhanced conservation and restoration within the watershed). These reduced hydropower operating costs also translate into cost savings for hydropower consumers, who may also be charged some of the cost difference to support forest protection and restoration.

Mechanisms like this example rely on the ability to meaningfully quantify and translate ecosystem services into estimates of tangible costs avoided by the financing actors (in this case, estimates of the dredging costs avoided by participating hydropower companies). Expanding such mechanisms to other as-yet-unmonetized co-benefits may require work to articulate, quantify, and monetize the impacts of these benefits through the lens of "nature-based solutions" – that is, with a focus on specific financial damages and risks that the conservation of forests can help avoid. In line with this, efforts such as the Taskforce for Nature-related Financial Disclosures (TNFD) may prove particularly valuable; this UN-supported working group is developing a framework to drive increased reporting and disclosure of nature-related financial risks and dependencies by corporations and other actors (TNFD, 2022). Such reporting would likely expand the awareness and salience of tangible impacts of forest conservation on business operations – setting the stage for increasing monetization and subsequent financing to reduce the risks created by forest loss. Similarly, the insurance industry is also considering opportunities in the nature-based solutions space, with forest insurance currently being the most advanced (Swiss Re Institute, 2021; Li, 2022).

Adopt a green alpha paradigm

While some of the tangible value that forests provide can be identified and quantified as discussed above, some value provided by forests have likely not yet been identified. Moreover, as discussed in the **Theoretical Framework** section, the total economic value per unit of forest is expected to increase over time, especially as additional forested land is lost. A methodology to estimate the scale of these yet-unrecognized and/or future value components could help incorporate them into market-based transactions and decision making. The *green alpha* methodology provides an estimation of the value of preserving forests for future use – that is, an option value enabling investors to account for this likely future appreciation of the total value of forests (see **Box IV.1**). Based on the *climate alpha* methodology explored in Golub et al., 2022, it provides a potential pathway for actors to monetize and internalize yet-unrecognized ecosystem-linked externalities of deforestation. This framework could also help investors assess the monetizable co-benefits of avoided deforestation to calculate future return on investment.

Box IV.1. The *green alpha* methodology

The *green alpha* methodology is an extension of what is presented in Golub et al. (2022) as the *climate alpha* valuation paradigm. Climate alpha reflects the extent to which the current market value of emissions reductions do not reflect the future appreciation (and monetization) of these assets. *Green alpha* describes a similar mismatch between current and future valuations of forest assets, and the potential gain from investing in forests prior to this future materialization of value. By nature, both *climate alpha* and *green alpha* formation are rooted in uncertainty regarding future climate policy. For example, strong signals of near-future strengthening of global climate policy would likely result in rapid appreciation of assets that help meet climate mitigation needs (and thereby comply with newly strengthened policies), including assets based on REDD+ activities. As current global emissions and deforestation trends are known to be at odds with global decarbonization goals, such shifts in climate policy could potentially occur at any moment. But the sequence of any policy course corrections, their timing, and the actual resulting increase of the shadow price of carbon are unknown. This suggests that investment in assets that will gain value in the face of future climate policy shifts could be lucrative, but the specific scale and timing of this expected jump in value can only be described using (at best) a probability distribution or event tree. By creating a long position on high-integrity REDD+ backed emission reductions, an investor could be positively exposed to future known risk premia up to the probability distribution. The economic value of this risk premium could be calculated as an option value, as detailed in Golub et al., 2022. The same logic applied to calculating *climate alpha* potentially applies to calculating *green alpha*, in that appreciation of main and co-benefits and resulting financial valuation could be estimated as a probability distribution.

Non-market-based opportunities for capturing additional co-benefits

Beyond the sphere of market-based mechanisms described above, a range of opportunities exist to leverage the co-benefits of forests to drive both investment and decision making in support of increased conservation. The diversity of forest co-benefits, and their potential impacts on human health, wealth, and welfare, create opportunities for alignment with unconventional sectors and stakeholders. Below, we discuss pathways to raise the effective valuation and visibility of forest co-benefits on policy agendas, focusing on the agricultural commodity and health sectors as two illustrative examples.

Promotion of deforestation due diligence within agricultural supply chains

While new means of measuring the tangible impacts of forest conversion to business operations may drive new financing mechanisms, emerging policies could create additional incentives for these companies to support forest protection. For example, compliance rules regarding deforestation in agricultural commodity supply chains are emerging in major export markets such as the European Union (EU Commission, 2022). Such rules could drive new corporate interest in supporting financial or programmatic mechanisms that protect forests from agricultural conversion. The Science Based Targets initiative (SBTi) also recently issued a new methodology to align forest, land, and agriculture related goals with their framework (SBTi, 2022). Setting targets under this initiative is becoming an increasingly common standard against which corporate actors are judged; moreover, policy signals suggest that setting standards under SBTi may eventually be functionally or literally mandated for some sectors or countries in the future (for example, US federal regulatory rulemaking initiated in late 2022, which proposes to require climate goals aligned with the SBTi framework for US federal suppliers and contractors above a certain contract size (OFCSO 2023).

Alignment of forest conservation goals with holistic health policy

As links between the natural world and human health outcomes become increasingly clear, policy-relevant definition of "health" are expanding. Strategically designed initiatives can help create willingness to avoid deforestation and indirectly compensate for opportunity loss of avoided deforestation by highlighting potential health implications of forests and their co-benefits. For example, the BC Parks Foundation in Canada recently launched PaRx, an initiative that aims to promote both conservation and healthcare savings by partnering with healthcare providers to issue "nature prescriptions" (PaRx, 2023). The prescriptions reduce barriers to nature access for patients (e.g., providing passes to parks), while highlighting the many health improvements linked to time spent in nature. Similarly, Japan has a long history of forest therapy programs, with evidence supporting positive economic and physical and mental health outcomes (Zhang et al., 2022). In addition to being supported by widespread local policy, these programs are embedded in the national health framework via the Ministry of Health, Labor, & Welfare and Ministry of Agriculture, Forestry & Fisheries.

At a broader level, the Health in All Policies (HiAP) concept, endorsed by United Nations Member States, provides an example of a framework for incorporating health implications into policies and decision making across all sectors – including, by extension, health impacts related to forest co-benefits. HiAP "takes into account the health implications of decisions, seeks synergies, and avoids harmful health impacts in order to improve population health and health equity" (WHO, 2013), and has been used at local, state, and national levels to enable the insertion of health priorities into policy actions at each. While such a framework provides a potential opportunity to advance forest conservation on the basis of its links to human health, it could also serve as a model for driving attention to a topic with implications that touch a diversity of sectors. For example, efforts might be made to promote a "Forests in All Policies" model, requiring the specific consideration of ecosystem impacts in a broader suite of policy decisions.

Box IV.2. Mobilizing funds for forests: The case for jurisdictional REDD+

Jurisdictional REDD+ (JREDD+) is a good example of collateral investment. Backed by public funds, institution building that allows a jurisdiction to scale up REDD+ supply in the future is probably one of the best ways to leverage private investment in emission reductions. The jurisdiction may use its resources to leverage this by directing REDD+ activities in areas where forest preservation, reforestation or prevention of forest degradation generates higher co-benefits (monetizable and non-monetizable). Accurate calculation of benefits at each implementation stage and by each stakeholder is necessary for cross leveraging and maximizing REDD+ benefits.

For practical reasons, there is still a need to draw the line between primary and collateral benefits. For example, corporations seeking high-quality high, integrity emission reductions (ERs) for compliance or as a part of voluntary actions could be willing to invest in JREDD+ to scale up ERs production. Understanding of co-benefits and EKC-like mechanisms and its monetization at the local level creates confidence in the permanence of ERs. This is because at some point, the direct incentives attributed to JREDD+ investment for ERs production will weaken and fade. When this happens, collateral benefits will play a major motivational role. For example, by estimating the co-benefits and assessing the chances that the local community and the host country will continue forest preservation in the future motivated by local benefits, the JREDD+ investor (e.g., corporation or investment fund) is better able to evaluate the risk of reversal.

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5. Conclusion

The gaps between total value, monetized value, and market prices create room for enormous losses of economic value (and total value) in the context of forest conservation, particularly when forests are viewed solely through the lens of their potential carbon benefits. Estimates of the *social cost of carbo*n are generally far higher than current global market prices of carbon, including those prices used in the context of carbon-based forest finance. If forest conservation is priced on the basis of its carbon impacts alone, the enormous value provided by forests through ecosystem services is excluded from decision frameworks that estimate value based on this pricing – which itself already elides the true social benefits of the carbon value itself. As such, under a carbon-only framework, the monetization of forest conservation programs, projects, and initiatives vastly undervalues the true benefits of these forests to society.

A global transition toward green growth will ultimately result in a reevaluation of the value of the environment and natural resources. To avoid future stranded assets and minimize regrets about the irreversible loss of ecosystem services, taking a forward-looking analysis of ecosystem value is essential. The future increase in the value of ecosystem services relative to conventional consumer goods must be considered, as well as other transformations potentially triggered by the shift toward green growth.

Moreover, to attract collateral investment, such forward-looking analysis must detect monetized and monetizable value in the investment, expressed in monetary terms. It is not just enough to compute environmental indicators: Investors are interested in what their potential monetary return may be on invested capital, as well as the risks. It remains difficult to measure, monitor, and verify many co-benefits. But the *social cost of deforestation* framework captures not only various components of economic and social benefits of forests, but also helps describe synergies and nonlinear responses of unit value to scale. Subsequently, the adoption of methodologies like green alpha valuation may help fill the gap in our near-term ability to monetize this complete value.

Using these approaches, we can assign financial weight to forest co-benefits, allowing them to be compared more easily to other goods. The goal is not to advance financial gain, but to elevate and leverage an expanded suite of forest co-benefits, across decision making frameworks and policy discussions that might otherwise eclipse what can't be represented in currency. A vital outcome of monetizing of forest co-benefits and connecting them to financial markets is the potential to unlock investment needed to support forest-positive actions. This can lay the groundwork for the collection of immediately available bridge funding resources from across sectors to complement REDD+ support, on the pathway toward a more all-encompassing framework and larger funding streams for health, biodiversity, and so on. The practical examples we discussed are already pushing the needle in the right direction.

Finally, we need to stop unsustainable nature-exploitative activities and capture true value of forests in decision making – not one or the other, but both. We must transform our value systems (held values) in societies, and policy and markets are an important political signal to catalyze this shift. However, even if a focus on co-benefits helps to accelerate investment in avoided deforestation, it still may be not enough to secure ambitious environmental targets. As such, the expansion of monetizable solutions must be reinforced by strengthening regulations. Future research should explore additional governance considerations and conditions for supporting increasing efforts to recognize forest co-benefits.

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V. CONCLUSION

V.1 Synthesis

According to the IPCC scenarios, we are running out of time to limit global warming to 1.5 degrees Celsius by the end of the century (IPCC, 2022). Meeting ambitious climate targets will necessitate drastic action and rapid emissions reductions. Thus, it important that we start taking concrete actions to meet and leverage available climate change mitigation opportunities. Nature-based solutions, in particular natural climate solutions, are examples of such opportunities. NCS, if implemented together with decarbonization in the energy and industrial sectors, are a powerful and cost-effective way to reduce emissions in the near-term (Anderson et al., 2019; Girardin et al., 2021). In addition, NbS hold the potential to contribute to many global challenges, including poverty alleviation and sustainable development (Anderson & Gough, 2022; Seddon et al., 2021). Still, despite recognition of the potential of NbS, there is a significant implementation gap (Chee et al., 2021; Sarabi et al., 2019). As such, this thesis was motivated by the clear need for research that is focused on accelerating the transformation from potential to implementation of NbS.

In the **Introduction**, I described four notable gaps in research on nature-based solutions: limited evidence synthesis on NbS, underrepresentation of the social sciences in high-level research on the environment, climate, and sustainability; lagging the mechanisms for unlocking NbS; and limited analyses that value the multiple benefits of NbS. Drawing on concepts, methods, and evidence from across disciplines in this thesis, my work brings together different ideas to shed new light on these outstanding issues. In doing so, I contribute to closing some of the aforementioned research gaps, thereby unlocking further channels for implementation. Specifically, **I add to research on NbS in three important ways** – with knowledge contributions, methodological contributions, and theoretical contributions:

- **Knowledge contributions.** All of the studies I undertook for this thesis have a literature synthesis component. A strength of this thesis is that it brings together information from different areas of research and practice. This allowed me to draw out trends and lessons that can be valuable in enhancing the implementation landscape for NbS. In addition, I contributed new insights to a long-ongoing debate around integration between social science research and modelling practices. I also help clarify the importance of valuing forests and some approaches to do so.

- **Methodological contributions**. This is particularly the case for the second study of this thesis, which focused on integration between the social sciences and modelling. While integration has often been called for in the literature, not as much attention has been given to why it is not done more. In my study, I elicited information directly from modellers and social scientists to help identify and overcome methodological barriers and bottlenecks to integration in the modelling process.
- **Theoretical contributions**. In the last study of this thesis, I introduced a new framework for capturing the current and future value of forest co-benefits. This framework builds on the existing theoretical literature and provides a foundation for application in natural ecosystems beyond forests.

To be more specific, in **Chapter VI.1**, "What influences the implementation of natural climate solutions? A systematic map and review of the evidence," I conducted a systematic review of the literature on NCS implementation. The study provided a comprehensive assessment of the literature on that topic, evaluating the literature on different types of NCS activities and mapping out what enabling factors for NCS implementation are mentioned where, and under what conditions. This study provided a broad contribution to the overall state of knowledge on NCS, and by proxy NbS, implementation. as few reviews then and even now and resulted in a large database of case studies and insights that are useful for guiding future research.

I find that the majority of studies we reviewed focused on tropical regions and forests. Furthermore, critical reflection is needed in knowledge production processes, including with and for whom, and with what objectives it takes place. Finally, while there are many important drivers of implementation, the engagement of indigenous peoples and local communities, performance-based finance, and provision of technical assistance are especially pertinent. However, it is usually not sufficient to have or address just one enabling factor at a time. Instead, implementation is often driven by bundles of enabling factors.

These insights from systematic review even guided the next steps of my own research. In **Chapter VI.2**, "Towards integration? Considering social aspects with large-scale computational models for nature-based solutions," I addressed one discussion point from the review, which is on how knowledge production processes are shaped. In the integration study, I focused on large-scale modelling processes, which are influential in producing knowledge for high-level processes and fora such as the IPCC assessments and UN Climate Change Conferences of the Parties. I find that, while integration is challenging, it remains a necessary endeavor. How integration takes place and who is involved – from experts to stakeholders – may depend on individual project conditions, resources, and objectives.

The role of performance-based finance supporting NCS implementation was also highlighted in my review. This is one reason I focused on financing as a component of **Chapter IV.3**, "Valuing the hidden benefits of forest-based climate change mitigation." In the study, I presented an economic framework for capturing the full value of forest benefits – or rather, the potential losses to society from deforested land – called the *social cost of deforestation* (*SCD*). The *SCD* consists of monetized benefits, (potentially) monetizable benefits, and non-monetizable benefits. In practice, ways of shifting monetizable benefits towards monetized are primarily rooted in creating and adapting financial instruments to incorporate their value into markets. Since not all value can be monetized, we also discuss how to close the gap between value and monetizable value by including the non-monetizable value of forests in the design of policies and other influential decision-making mechanisms. Additionally, the study offers some emerging real-word examples, ultimately aiming to foster three avenues of progress: (1) to avoid socially and environmentally suboptimal outcomes that naturally emerge from a carbon-centric approach, (2) to support policy making and dialogue in better capturing the co-benefits of forests; and (3) to unlock more finance for forest-positive actions, acknowledging that many private and institutional investors are interested or even obliged to ground their portfolios in a wider sustainability spectrum.

The above paragraphs describe how I met the core objective of this thesis: to conduct policy-relevant research to advance the implementation of NbS. To make the connection to NbS implementation, and between the different studies, I conceptually placed my research approach together with theory on the policy process and evidence-based policymaking (Bowen & Zwi, 2005; Jann & Wegrich, 2006). I argue these are useful heuristics for mapping out how to go from NbS potential, such as a policy or activity idea, to implementation. Underlying the stages between potential and implementation are the three fundamental building blocks of knowledge synthesis, planning and decision-making, and policy and financing mechanisms. This thesis contributes to all three though the synthesis methods used in the research activities as well as the research results, which can help inform good planning and decision-making and the effective design of policy and financing mechanisms.

Last, while I come at this research from a disciplinary starting point as a doctoral candidate in Geography, I use this thesis as an opportunity to reflect on what it means to be a part of the field of Geography. As an interdisciplinary researcher with a background in biology, anthropology, and public policy, I am probably not the "traditional" geographer who comes to mind when one thinks of the term, in the old school sense of the word. But in a world where pressing research questions demand interdisciplinary answers, who is anymore? As described in the **Geography: A field for today's challenges** section, Given the cross-cutting nature of my work and how the field of geography has developed in flexible ways over time, it seems a fitting place home for me – at least for now – and my doctoral work.

V.2 Outlook

Looking to the future, there are a number of research and policy implications that can be extrapolated from this thesis. Below, I start by describing outstanding research needs and directions. I highlight opportunities for methodological developments and thematic issues that were outside the scope of this thesis, but deserve greater attention. I follow this with a few examples of potential policy recommendations that are relevant to NbS implementation, informed by the outputs of this thesis.

On the research side, there is space and need to further refine and expand the use of systematic methods to tackle the complexities of NbS. Systematic reviews are one aspect of this. Systematic methods for collecting, analyzing and comparing data and evidence on NbS could be valuable for ensuring a level of harmonization and comparability between research areas. Living systematic review methods could also be useful to explore (Elliot et al., 2021). With living systematic reviews, researchers predefine and follow a rigorous protocol, regularly updating evidence on a topic based on the latest information. With a constantly changing and growing policy and research landscape on NbS, these reviews could provide a way to ensure that the most recent and up-to-date information is being compiled, reported on, and used to inform decisions. In addition, these systematic approaches could contribute directly to improving the integration of social science research and large-scale modelling by providing a wide-ranging suite of data and evidence that could be used as inputs to the model or for setting model constraints. It would be interesting to pursue some further research on this topic where the insights from **Chapter IV.2**, my study on integration, are actually tested and operationalized.

Furthermore, there is opportunity for deeper research on the role nature-based solutions can play in a just transition, which would mean that the transition to a green economy is done in a way that is fair and equitable. This requires more granular contextual research on areas where NbS could be implemented, the trade-offs and side effects, and perceptions and priorities of relevant stakeholders. My thesis, for example, demonstrated that there are large differences in the geographies and NCS activities that covered in the available literature on implementation. While my thesis ended up having a broad, global focus, my original pre-COVD-19 proposal was to use my mapping of the literature in **Chapter VI.1** to identify two underresearched areas in which I would have undertaken in-depth fieldwork and case studies on the dynamics surrounding NCS implementation. This could still be worth following up on in a future project.

Another important structural step that can influence views on fairness and equity is ensuring that a diversity of perspectives are represented in research, from the stages of identification of the question, to the design, as well as interpretation of results, as discussed in **Chapters VI.1** and **VI.2**. Transdisciplinary research, which is conducted in tandem with non-academic stakeholders, offers one avenue for achieving more balanced outcomes. Additionally, engaging stakeholders early on can help target research efforts on areas that are of interest to them for practical reasons, such as when making decisions about where to prioritize invest or implement a new NbS activity.

In terms of the policy implications, there continues to be growing demand for rigorous synthesis work and evidence-based policymaking. This is certainly the case when it comes to developing solutions to address global grand challenges such climate change mitigation, poverty alleviation, and environmental protection. The United Nations Development Programme, for example, recently launched a Global Coalition for SDG Syntheses. It aims to "generate syntheses organized around the five SDG pillars (people, planet, prosperity, peace and partnership), to identify lessons and make policy recommendations for accelerating results in the final years of the SDGs" (UNDP, n.d.). Similarly, the United States Biden-Harris Administration launched a White House "Year of Evidence for Action" in April 2022. The initiative aims to promote sharing of leading practices to achieve healthier and more equitable outcomes for the American people, strengthen structures to promote evidence-based decision-making, and increase cross-sectoral connections and collaborations, e.g., between researchers and the government (Eller et al., 2022).

Furthermore, based on the results of this thesis, I underscore three policy insights:

- **Investing in NbS means investing in local people**. This can include mechanisms to pay them for implementing NbS, training them to build technical capacity, and engaging them in the design of NbS and with the knowledge that they bring to the table. As **Chapter IV.1** showed, those are all crucial facets of implementation.
- **Funding and support for interdisciplinary and participatory research is essential**. As **Chapter IV.2** noted, for example, there are limits to computational models. While valuable for answering certain research questions, there is a need to look to other disciplines and methods to fill gaps, address uncertainties, and reduce bias in the knowledge production process.
- **We must think holistically about NbS, now and in the future.** The value of nature is infinite. While some values of nature, even if unquantifiable, we can easily identify now, there may be other value nature holds that we are currently not even aware of, and that only may come to light in the future as new scientific discoveries are made. As such, frameworks such as the one we propose in **Chapter IV.3** are useful for NbS in the bigger picture of global change dynamics.

Finally, nature-based solutions are just one of many actions that need to be implemented to address climate change. Similarly, climate change mitigation is just one significant contribution that nature-based solutions can make to society. Yet, there is still a long way to go before we have fully unleashed the potential and opportunities of NbS. At the same time, every day we learn a little more that gets us closer to a world where nature-based solutions are practiced at scale. Today, this thesis contributed to some of that learning.

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Appendix

A.1 Supplementary Information for Chapter IV.1

S1. Review protocol

The systematic review followed three main steps: literature search, abstract screening, and review and coding of data from selected studies. For the literature search, the project team developed a search criteria based on the definition of natural climate solutions and key words in our research question (**Figure S1**). A few different combinations of search terms were iterated on and evaluated based on the first ten search results, until the project team agreed on a query that provided the greatest number of relevant results.

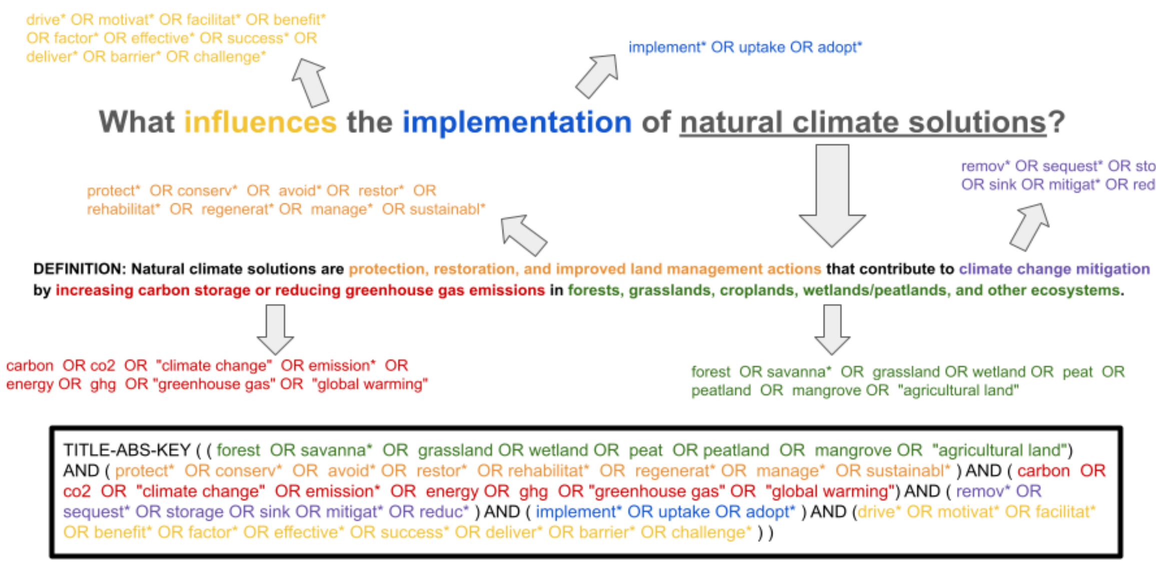

Figure S1. Breakdown of search query.

Once the search query was determined, the project team developed and agreed on a set of inclusion and exclusion criteria for the review (**Table S1**). These were tested on a random sample of search results and discussed amongst the screening team to ensure a common understanding of the criteria. The search query was limited to Web of Science and Scopus.

Table S1. Review search query and inclusion/exclusion criteria

Search query	TITLE-ABS-KEY ((forest OR savanna* OR wetland OR peat OR peatland OR mangrove OR "agricultural land" OR "grassland") AND (protect* OR conserv* OR avoid* OR restor* OR rehabilitat* OR regenerat* OR manage* OR sustainabl*) AND (carbon OR co2 OR "climate change" OR emission* OR energy OR ghg OR "greenhouse gas" OR "global warming") AND (remov* OR sequest* OR storage OR sink OR mitigat* OR reduc*) AND (implement* OR uptake OR adopt*) AND (drive* OR motivat* OR facilitat* OR benefit* OR factor* OR effective* OR success* OR deliver* OR barrier* OR challenge*))
Inclusion criteria	- Studies related to activities that qualify as NCS - Studies on implementation context, including barriers and enablers, failures and successes
Exclusion criteria for subject areas	- Engineering - Biochemistry, Genetics, and Molecular Biology - Computer Science - Chemical Engineering - Physics and Astronomy - Mathematics - Chemistry - Materials Science - Pharmacology, Toxicology and Pharmaceutics - Veterinary - Immunology and Microbiology - Neuroscience - Nursing
Manual exclusion criteria	- Studies that do not focus on at least one NCS activity (e.g. that focus on other technologies or activities; flora and fauna) - Studies on activities not yet implemented - Studies that are simulations or models of possible activities and potentials - Studies on adaptation (vs. mitigation) - Systematic reviews and meta-analyses - Studies on specific to technical aspects of implementation - Studies that are not about an enabling factor (e.g. about the mode of implementation)

The project team used an automated scoping platform to import the abstracts of the search results for review. Each member of the screening team was randomly allocated abstracts (with titles) to review and apply the inclusion and exclusion criteria to. After screening all the abstracts, the included articles were reviewed using the full-text. Each article was coded based on a pre-defined codebook (see section **S2**).

In reading the full-texts, a small number of articles were additionally excluded after it was determined that they either did not meet the inclusion criteria or they met exclusion criteria. In most cases, this was because the abstracts did not provide enough information to determine if they met the criteria during the initial literature screening. The full flow of the literature scoping and screening is illustrated in **Figure S2**.

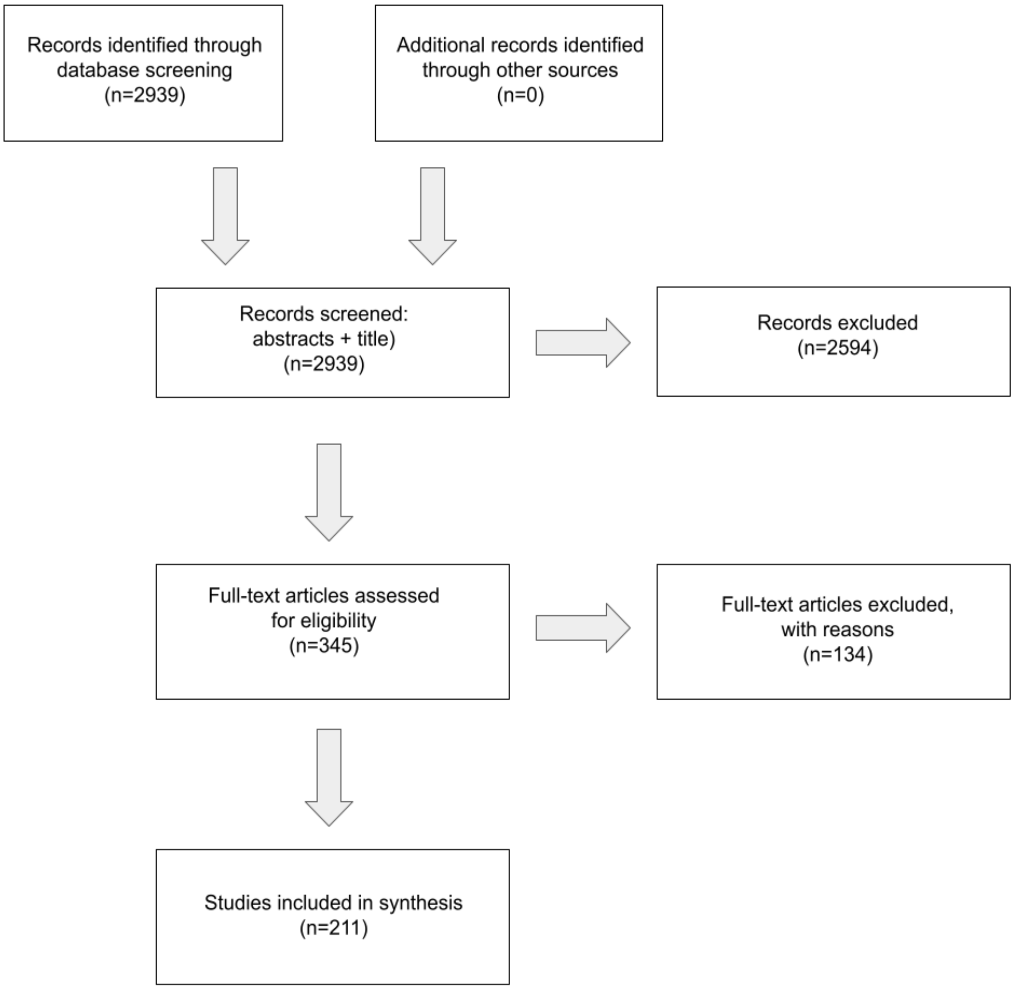

Figure S2. Process for literature screening, adapted from PRISMA flow chart (Adapted from Page et al (2021). CC BY 4.0).

S2. Review codebook

To ensure that data was extracted and coded from the literature uniformly, the project team developed a codebook of information to be recorded (**Table S2**). These included background information, such as the publication year, general research methodologies used, research locations, land types, land uses, co-benefits, and enabling factors. These codes were recorded in an excel sheet with a dropdown menu presenting all the coding options. A blank column was also available next to each category of enabling factor for the coder to provide explanations for how they coded factors where relevant.

The initial set of enabling factors was quite broad and based on factors that appeared frequently in literature on implementation. These enabling factors were re-coded by the screening team during analysis because during the coding process some of the factors were found to be repetitive of each other (**Table S3)**. When factors were grouped during the re-coding, papers mentioning multiple factors that had been grouped together only received one entry for the new factor to avoid double counting. The disaggregated information, however, was still used for sub-sample analysis on some factors with many mentions, such as engagement of Indigenous Peoples and Local Communities (IPLC), performance-based finance, and technical assistance. Similarly, savannahs and grasslands were combined for the analysis and entered in the same way to avoid double counting.

Table S2. Codebook for data extraction

General methodolog(ies)	**Research location: World region(s)**	**Research location: Countr(ies)**	**Research location: Sub-national region(s)**
Ethnographic case studies	Global	Global	Manual entry
Semi-structured interviews	NA (North America)	Afghanistan	
Focus groups	LATAM (Latin America, Caribbean)	Albania	
Participant observation	EU (Europe, Central Asia, Russia)	Algeria	
Comparative review	SSA (Sub-Saharan Africa)	Andorra	
Desk review	MENA (Middle East, North Africa)	Angola	
Validation workshops	EA (East Asia)	Antigua and Barbuda	
Thematic analysis	SA (South Asia)	Argentina	
Literature review	SEA (Southeast Asia)	Armenia	
Photovoice	OC (Oceania)	Australia	
Ecosystem sampling		Austria	
Statistical analysis		Azerbaijan	
Modelling		Bahamas	
Survey		Bahrain	
Remote sensing		Bangladesh	
Structured interviews		Barbados	
Case studies		Belarus	
Qualitative analysis		Belgium	
Semi-quantitative analysis		Belize	
Logic analysis		Benin	
Social network analysis		Bhutan	
Field experiment		Bolivia	
Participatory methods		Bosnia and Herzegovina	
Multi-criteria analysis		Botswana	
Impact evaluation		Brazil	
Choice Experiment		Brunei	
Policy network analysis		Bulgaria	
Discourse analysis		Burkina Faso	
		(**remaining countries listed alphabetically...)**	

Land type(s)	Previous land use(s)	NCS activit(ies)	Progam/Initiative(s)
Forest	Not mentioned	Reforestation	None
Grassland	Agriculture - unspecified	Afforestation	REDD+
Wetland	Cropland	Natural regeneration	CDM
Savannah	Pasture/grazing	Agroforestry	JI
Agriculture	Agro-silvo-pastoral system	Avoided forest conversion	Jurisdictional
Peatland	Shifting cultivation/fallow	Natural forest management	20 x 20
	Aquaculture	Improved plantations	GEF
	Tree monocrop/plantation	Avoided woodfuel	FIP
	Deforested (clear cut)	Fire management	Bonn Challenge
	Degraded	Biochar	National Forest Conservation Program (NFCP)
	Land used for extractives	Trees in croplands	Three-North Shelter Forest Program
	Fire	Nutrient management	Common Agricultural Policy (CAP)
	Non-fire natural disturbance	Grazing - feed	AFR100
	Marginal and/or abandoned land	Conservation agriculture	Grain to Green Program (GTGP)
	Forest land	Improved rice	Return Farmland to Forest Program (RFFP)
		Grazing - animal management	Conversion of Cropland to Forestland (CCFP)
		Grazing - optimal int.	Nation Forest Protection Program (NFPP)
		Grazing - legumes	Productive Safety Net Program
		Avoided grassland conversion	EWFP
		Coastal restoration	
		Peat restoration	
		Avoided peat impacts	
		Avoided coastal impacts	
		Silvopasture	
		River Restoration	
		Wetland Restoration	
		Improved forest management	
		Not specified	

Implementing institution(s)	Co-benefit(s)	Enabling factors	
		Social	Economic
Government	Community rights	Stakeholder consultation	Delivery of benefits
NGO	Local livelihoods	FPIC	Labor availability - general
University	Biodiversity conservation	Provision of co-benefits	Labor availability - qualified
Company	Carbon sequestration	Local awareness	Market competitiveness
Community	Air purification	Education	Market access
Individuals	Water	Local support - general	Infrastructure
Unclear	Soil erosion prevention	Local support - trust	Accessibility to location
N/A	Landslide prevention	Local support - confidence	

Not mentioned	Forest therapy/regeneration	Consistent quality of life	
	Capacity building - communities	Traditional values	
	Increased soil fertility	Clear carbon rights	
	Accumulation of forest nutrients	Alignment of needs and benefits	
	Ecosystem resilience	Participation of IPLCs	
	Community resilience	Acceptance of local norms	
	Enterprise benefits		
	Governmental income		

Enabling factors (continued…)				
Political	**Institutional**	**Financial**	**Technical**	**Biophysical**
Enforcement	Realistic requirements	International donor finance	Compatible practices	Adequate soil
Secure land and property rights	Regulatory support	Appropriate incentives	Technology accessibility	Native species
Lack of corruption	Transparency	Payments for ecosystem services	Technical assistance	Genetic diversity
Collaboration	Policy coordination	Investment	Information provision	Climate
Governance	Good legal frameworks	Access to financial services	Availability of seeds and seedlings	Size of protect area/nature reserve
Clear authority	Strong institutional frameworks	Performance-based finance	Training	Forest yield
Access to justice	Diversity of regulations	Benefit-sharing mechanisms	Adoption of integrated approach	Biodiversity of habitats
Recognition of customary rights	Aligned standards and local laws	Secure funding	Identification of land-use drivers	Surrounding land use
	Federal, state, municipal programs		Assessment of ecological conditions	Potential for increasing carbon stocks
	Proper management		MRV strategies	
			Mapping	
			Adequate capacities	
			Planning	
			Research	

Table S3. Re-coded groupings of enabling factors for analysis

	Old factors	**New factors**
Social	Local support + Alignment of needs and benefits + Consistent quality of life + Provision of co-benefits	**Acceptance (local)**
	FPIC	**FPIC**
	Participation of IPLCs + Local awareness + Education	**IPLC engagement**
	Stakeholder consultation	**Stakeholder consultation**
	Traditional values + Local norms	**Recognition of traditional values**
	Clear carbon rights	**Clear carbon rights**
Economic	Infrastructure + Accessibility + Market access	**Accessibility**
	Market competitiveness	**Market competitiveness**
	Delivery of benefits	**Delivery of benefits**

	Labor	**Labor availability**
Political	Good governance (political will)	**Acceptance (leadership)**
	Collaboration + Policy coordination (between sectors, or within a sector) + Aligned standards and local laws	**Collaboration/ coordination**
	Lack of corruption + Proper management	**Integrity**
	Clear authority + Access to justice	**Accountability**
	Transparency	**Transparency**
Institutional	Secure land and property rights + Recognition of customary rights	**Land/customary rights**
	Good legal frameworks + Strong institutional frameworks	**Frameworks**
	Regulatory support	**Regulatory support**
	Diversity of regulations + Federal, state, municipal programs + Realistic requirements	**Realistic requirements**
	Enforcement	**Enforcement**
Financial	International donor finance	**Donor finance**
	Appropriate incentives + Payments for ecosystem services + Performance-based finance + Benefit-sharing mechanisms	**Performance-based finance**
	Secure funding + Investment	**Secure funding**
	Access to financial services	**Financial services**
Technical	Technical assistance + Information provision + Training + Availability of seeds and seedlings + Technology accessibility + Adequate capacities	**Technical assistance**
	Compatible practices + Adoption of integrated approach	**Compatible practices**
	Mapping + Planning + Identification of land-use drivers + Assessment of ecological conditions	**Land use planning**
	MRV strategies	**MRV strategies**
	Research	**Research**
Biophysical	Native species + Genetic diversity + Biodiversity of habitats	**Species diversity**
	Potential for increasing carbon stocks	**Carbon stock potential**
	Climate + Adequate soil	**Climatic conditions**
	Size of protect area/nature reserve + Surrounding land use + Forest yield (Land use)	**Land conditions**

S3. Supplementary analysis for Figure 1.1

In **Figure 1.1**, we presented the growth trajectory of the literature on NCS based on number of publications per year. We also illustrated the change in literature separated into coverage of protection, restoration, and management activities. Most papers in the dataset touched on at least two categories of NCS activities, so these articles are plotted once for each category they reference in **Figure 1.1**. Here, we plot the publications that only focus on one category of NCS (**Figure S3**). This is 14 publications for protection activities, 17 for restoration activities, and 17 for management activities (**Table S4**). This lower number of papers on individual categories of NCS highlights that these are not always an explicit focus and points to the importance of broadening search scopes to find information on different activities. Note these numbers of publications may be slightly less than the number of observations on only protection, restoration, and management categories described in the main article text because some papers contained multiple observations.

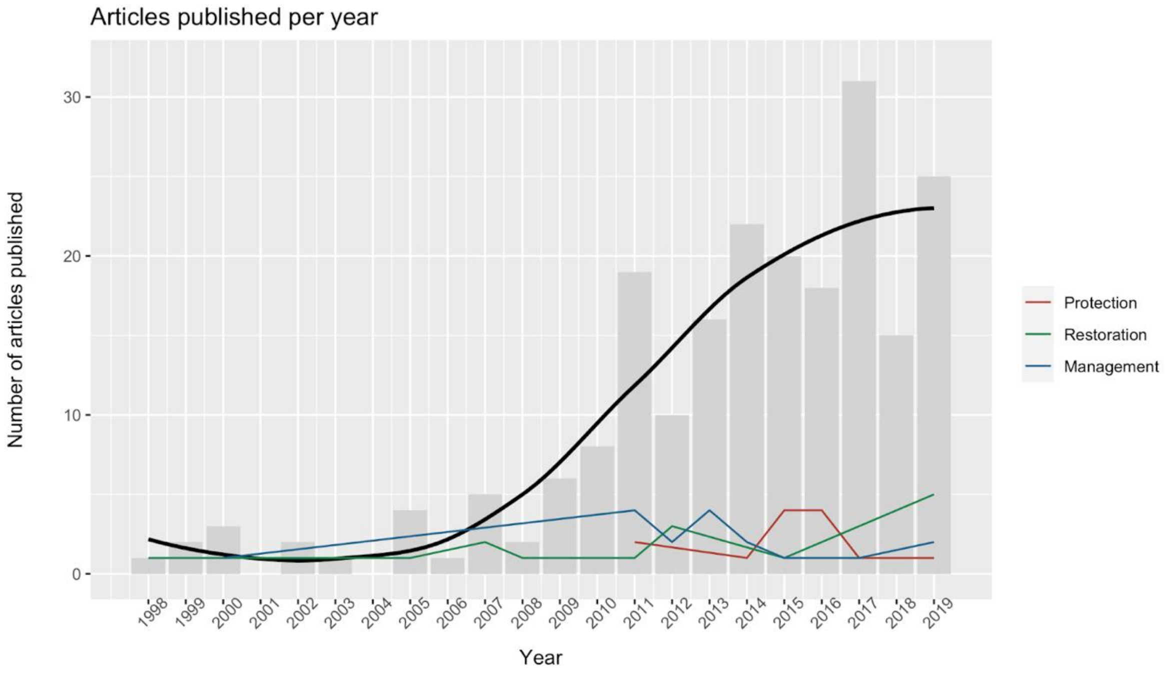

Figure S3. Growth in number of articles on natural climate solutions (NCS) published per year through November 2019 (N=211), including number of mentions of activities falling into different categories of NCS (only protection (n=14), only restoration (n=17), or only management (n=17)) each year.

Table S4. Number of publications on only protection, restoration, or management categories of NCS per year from 1998-2019

Year	Protection	Restoration	Management
1998	0	1	0
1999	0	0	0
2000	0	0	1
2001	0	0	0
2002	0	0	0
2003	0	0	0
2004	0	0	0
2005	0	1	0
2006	0	0	0
2007	0	2	0
2008	0	1	0
2009	0	0	0
2010	0	0	0
2011	2	1	4
2012	0	3	2
2013	0	0	4
2014	1	0	2
2015	4	1	1
2016	4	2	0
2017	1	0	1
2018	1	0	0
2019	1	5	2

S4. Supplementary analysis for Figure 1.9

We observed interesting differences when we plotted simple correlation matrices of the enabling factors for the four largest regional subsets of data (Latin America, Sub-Saharan Africa, Southeast Asia, and South Asia) (**Figure S4**). The results, however, do not imply causation but show factors that are mentioned in tandem in the literature. Further analysis and a greater sample size are needed to draw concrete conclusions. Nevertheless, these matrices can provide a useful basis for opening up further discussion. Specifically, we noted variation in the combinations of factors that are significantly correlated and the strength of these correlations between regions. A selection is described below.

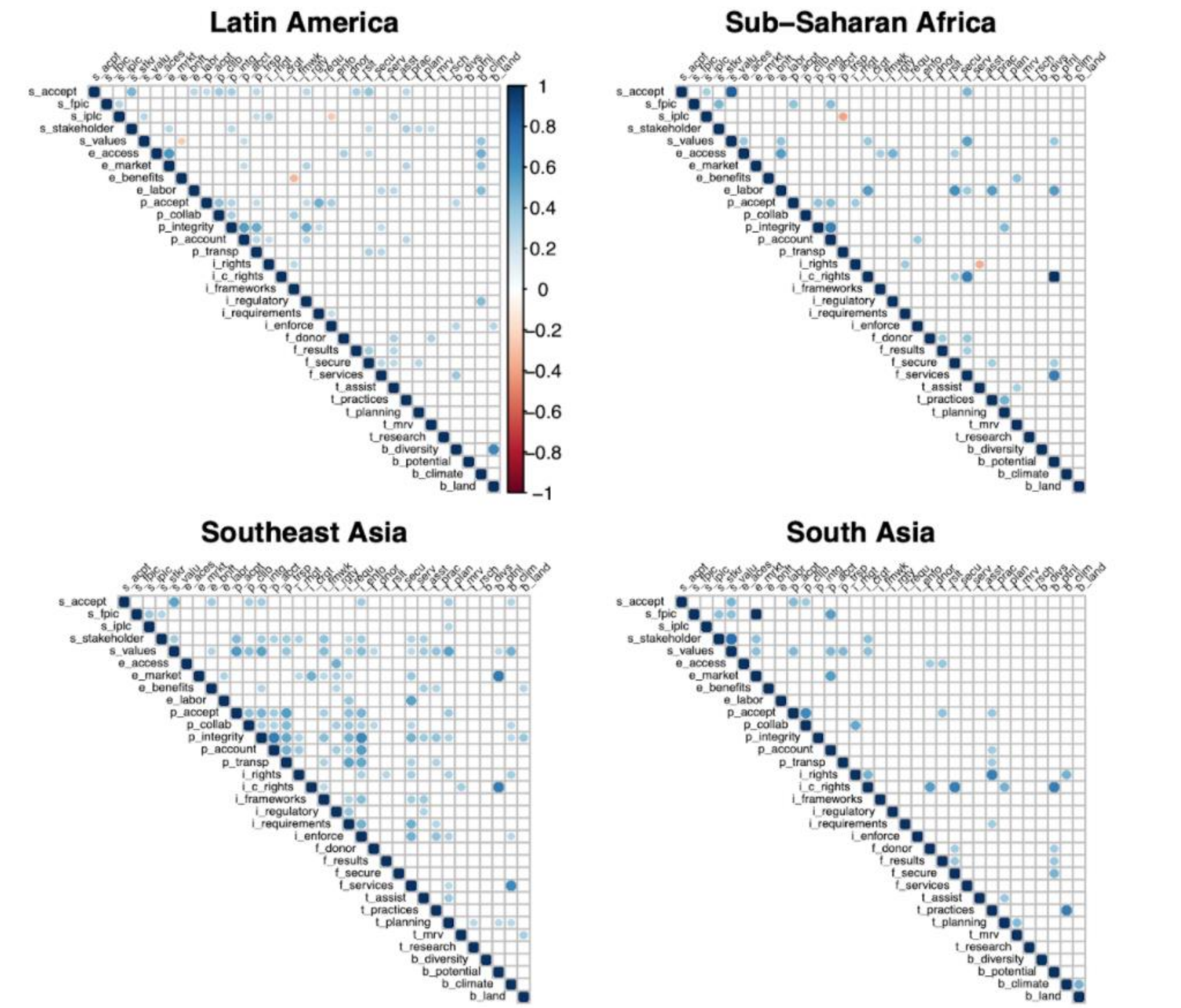

Figure S4. Correlation matrices by region.

Latin America. The results for this region suggest that political and institutional factors are closely linked. Political integrity is correlated with accountability and transparency, as well as having regulations in place. Political acceptance (i.e. from leadership) is also correlated with the latter.

Local acceptance (i.e. from IPLCs) is an important factor and correlated with a number of others: stakeholder consultation, secure funding, labor availability, collaboration, and also political acceptance, integrity, and transparency. We observe a weak negative correlation between the delivery of economic benefits and having strong frameworks in place and IPLC engagement and enforcement. The first trade-off may be because in some cases frameworks that are too complex may hinder the implementation of NCS that would lead to livelihoods and income benefits (Rosa da Conceição et al., 2018). The second may be explained by potential tensions that may arise when determining traditional and legal areas of jurisdiction and how and who should rule them (Ellis et al., 2015).

Sub-Saharan Africa. The strongest correlations in this region were between carbon rights and biophysical potential as well as recognition of traditional and local values and local acceptance. The high weighting for the latter may be related to the limited number of observations with those factors. Local acceptance, however, was also correlated with IPLC engagement and financial services. This combination of factors reflects calls in the literature for equitable distribution of financial incentives and access to financing that meets the needs of local communities (Barr & Sayer, 2012). Similarly, labor availability was correlated with secure funding and compatible practices. This again demonstrates how a range of factors go hand in hand with each other. For example, financing is needed to implement projects, but project requirements must also be flexible to local capacities for implementation to take hold (Chia et al., 2019).

Southeast Asia. A major difference in the results of SEA compared to the other regions is the number of significant correlations generally, but in particular among the political and institutional factors. Realistic requirements and enforcement are both factors that appear together with a number of others, including collaboration and coordination, transparency, accountability, and integrity. These results align with some of the power inequities described in the literature. In Indonesia, for example, lack of buy-in for REDD+, as well as the difficulty of competing with mining and palm oil production, remain significant challenges to implementation and adherence of NCS activities (Enrici & Hubacek, 2019). Historically, the country has also suffered from corruption and fraud in the sector with forestry companies receiving incentives for reforestation but using them for monoculture plantations or activities that led to loss of biodiversity (Barr & Sayer, 2012). In Vietnam, vertical policy coherence is also a systemic issue that carries over to communications, staffing, and financing (Wurtzebach et al., 2019).

South Asia. The correlations in this region indicate that FPIC is important, or has been a prominent part of the implementation narrative. Market competitiveness, stakeholder consultation, recognition of traditional values, and accountability are also relevant where FPIC is mentioned. These factors reflect again the need to balance NCS activities with local needs and alternative income sources. A study in Nepal on REDD+, for example, found mixed responses as to whether the programme is beneficial to community members and overall decreasing optimism and increasing concerns about forest user rights and other elements of governance due to corruption and imbalances of power (Bastakoti & Davidsen, 2017). Similarly, in Bangladesh while illegal logging has been reduced it remains an ongoing issue with local officials partaking in bribery (Rahman & Miah, 2017). Co-management projects in the country did see success in tackling the issue when efforts were made to rehabilitate former illegal loggers and poachers in new activities to earn income such as involving them in community forest patrolling groups. These projects bring together communities and members of the government and forestry department; however, additional challenges include loss of traditional community rights and forest access as well as mistrust and project ownership conflicts.

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A.2 Supplementary Information for Chapter IV.2

Table S5. Semi-structured interview questions

Field of inquiry	Interview questions		
	IAM modellers	*NbS/topical experts*	*Methodology experts*
Background information	What is your current position?	What is your current position?	What is your current position?
	Years of relevant experience?	Years of relevant experience?	Years of relevant experience?
	Examples of relevant projects/experiences?	Examples of relevant projects/experiences?	Examples of relevant projects/experiences?
	Which large-scale models/IAMs do you work with?	What kind of models do you usually use in your research activities?	What kind of models do you usually use in your research activities?
	Purpose of large-scale models/IAMs? For NbS?	What is the purpose of the models that you use?	What is the purpose of the models that you use?
		Do you work with large-scale models/IAMs? How do they interact with the other models you previously mentioned?	Do you work with large-scale models/IAMs? How do they interact with the other models you previously mentioned?
		Purpose of these types of models? For NbS?	Purpose of large-scale models/IAMs?
Role of social preferences	What role does social preferences have in NbS?	What role does social preferences have in NbS?	What role does social preferences have in the topics that you have been researching?
	How do you rate the significance of considering social preference in NbS compared to other dimensions/aspects in your research?	How do you rate the significance of considering social preference in NbS compared to other dimensions/aspects in your research?	How do you rate the significance of considering social preference compared to other dimensions/aspects in your research?
	How are you (or other work you're familiar with) including social preferences in your	How are you (or other work you're familiar with) including social preferences in your	How are you (or other work you're familiar with) including social preferences in your

	research? What's the purpose/value?	research? What's the purpose/value?	research? What's the purpose/value?
	Is this approach sufficient or sub-optimal? What would be the ideal approach?	Is this approach sufficient or sub-optimal? What would be the ideal approach?	Is this approach sufficient or sub-optimal? What would be the ideal approach?
Engaging with actors/stakeholders	How do you engage with people/stakeholders as a source of information?	How do you engage with people/stakeholders as a source of information?	How do you engage with people/stakeholders as a source of information?
	How ready are they to provide the information that you require?	How ready are they to provide the information that you require?	How ready are they to provide the information that you require?
	What would be needed to allow you elicit the required information from stakeholders? Specific methods?	What would be needed to allow you elicit the required information from stakeholders? Specific methods?	What would be needed to allow you elicit the required information from stakeholders? Specific methods?
	In your experience, to what extent does the information obtained from stakeholders get adopted/incorporated into your research work?	In your experience, to what extent does the information obtained from stakeholders get adopted/incorporated into your research work?	In your experience, to what extent does the information obtained from stakeholders get adopted/incorporated into your research work?
Integration into modelling process	Can you describe how the models that you use utilize/assess/consider social preference related issues/information?	Can you describe how the models that you use utilize/assess/consider social preference related issues/information?	Can you describe how the models that you use utilize/assess/consider social preference related issues/information?
	Is social preference a formalized element in your model (i.e. part of equation or parameter)? If yes, please describe	Is social preference a formalized element in your model (i.e. part of equation or parameter)? If yes, please describe	Is social preference a formalized element in your model (i.e. part of equation or parameter)? If yes, please describe
	If not, how are you still incorporating social preference in your use of the model?	If not, how are you still incorporating social preference in your use of the model?	If not, can social preference still be incorporated in your use of the model?
	Is this approach sufficient or sub-optimal? What would be the ideal approach?	Is this approach sufficient or sub-optimal? What would be the ideal approach?	Is this approach sufficient or sub-optimal? What would be the ideal approach?

A.3 Supplementary Information for Chapter IV.3

Plan Vivo, whose methodology requires quantification and monitoring of all ecosystem services, assessment of livelihood impacts, and development of a *payments for ecosystem services* agreement with project participants. In addition, the Plan Vivo Certificate (PVC) benefit-sharing mechanism commits at least 60% of the proceeds from PVCs to project participants, who are often from poor rural communities. TREES sets its environmental, social, and governance requirements in line with the Cancún Safeguards, which are seven safeguards that were agreed upon in 2010 by Parties to the United Nations Framework Convention on Climate Change to mitigate potential risks from REDD+. These safeguards include participation of and respect for indigenous peoples and local communities, addressing the risks of reversals, and the conservation of biological biodiversity.

Specific co-benefits were not outlined within the protocols of VCS, Gold Standard, or CAR. The technical and methodological guidance of the carbon standards focuses primarily on the quantification of project greenhouse gas benefits and how to set baselines and additionality for those. As mentioned previously, however, the VCS and the Gold Standard set out other environmental and social requirements via complementary standards. Co-benefit standards often have a broader objective than carbon standards and focus on additional benefits of forests beyond greenhouse gas removals. For example, VCS' Climate, Community, and Biodiversity Standards requires that projects integrate measures that ensure all stakeholders are fully engaged, customary and statutory rights are respected, and high conservation value lands are maintained, amongst other things. Similarly, the Gold Standard's official certification body is SustainCERT, through which it is possible for a project to certify additional SDG impacts. The Gold Standard also has partnered with Fairtrade International on the Fairtrade Climate Standard, which aims to support smallholders and farmers in gaining access to carbon market benefits.

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