Global climate governance:

The politics of terrestrial carbon mitigation in the Paris Agreement

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Abstract

Emissions from land have been only partially included to date within the United Nations Framework Convention on Climate Change and its Kyoto Protocol. Under the 2015 Paris Agreement, nations have committed to preventing dangerous global warming with an objective to 'balance emissions from sources and removals from sinks' in the second half of this century, raising the possibility of unprecedented reliance on land-based mitigation. The objective further requires that this balance must be achieved 'on the basis of equity and in the context of sustainable development and poverty eradication'.

Modelled scenarios for achieving the 'balance' objective of the Paris Agreement rely on drawing carbon dioxide from the atmosphere via photosynthesis and storing it in land-based sinks or underground, potentially reducing the availability of productive agricultural land, and encroaching on natural land. However these issues are poorly recognized in the policy-uptake of modelled outputs. This thesis analyses the contested politics of including (and accounting for) land-based mitigation in a post-2020 climate agreement, and the consequences for future mitigation pathways over the course of this century.

Science enables better understanding of climate change causes and impacts, with climate policy heavily reliant on scientific legitimization. This thesis takes a threefold approach to understanding the legitimization of policy through practices of science: first, by analyzing land-use accounting rules as a site of politics under the climate regime; second, by using a co-production lens to explain the legitimization of negative emissions as key mitigation options; third, by assessing the synergies between land-based carbon removal and sustainable development goals, using a risk evaluation framework.

It finds that the legitimization of a technical or 'expert-led' approach to climate governance in the context of the Paris Agreement has so far led to an expectation for unprecedented reliance on the land sector to meet the 'balance' goal in the long-term mitigation objective, implying strong trade-offs with other societal goals.

The thesis concludes that the Paris Agreement institutionalizes similar dynamics to the Kyoto Protocol, taking a technocratic approach to land-sector governance, where the perception of model-based knowledge as 'objective science' lends authority to outcomes that might otherwise be more critically debated and contested. Closer engagement between modellers and policy experts for mitigation scenario development would allow for more negotiated forms of knowledge production, that might better clarify and represent the multiple objectives and interests at stake in the utilization of limited land resources.

These findings highlight the need to make explicit the values and assumptions embedded in the co-production of science and policy, and how accounting for societal values becomes a mutual responsibility for scientists and policy-makers.

Declaration

This is to certify that:

(i) the thesis comprises only my original work towards the PhD, except where indicated in the preface,

(ii) Due acknowledgement has been made in the text to all other materials used,

(iii) the thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Kate Dooley
August 2018

Preface

Kate Dooley was the primary researcher and author for all chapters in this thesis, including the planning and execution of the research project. Some of the work included in this thesis was carried out with other authors, in the form of published journal articles. Publication details are listed below. The inclusion of these publications into the thesis has been approved by the advisory committee. The primary supervisor, Peter Christoff, has signed the University of Melbourne Declaration for a thesis with publication. All co-authors have signed the University of Melbourne co-author declaration form attesting that Kate Dooley contributed more than 50% to each publication.

Publications arising from this PhD thesis:

Chapter 4

Title: Governing by expertise: The contested politics of (accounting for) land-based mitigation in a new climate agreement
Authors: Dooley, K., & Gupta, A.
Journal: International Environmental Agreements: Politics, Law and Economics
Year, volume, pages: 2017, 17(4), 483-500.
Candidates contribution: 70%

Chapter 5

Title: Co-producing climate policy: negative emissions, land-use and sustainable futures
Authors: Dooley K, Christoff P, & Nicholas KA.
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Year, volume, pages: 2018, 1(e3), 1–10.
Candidates contribution: 70%

Chapter 6

Authors: Dooley, K., & Kartha, S.

Title: Land-based negative emissions: risks for climate mitigation and impacts on sustainable development

Journal: International Environmental Agreements*:* Politics, Law and Economics

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Candidates contribution: 70%

In addition, the following publications were produced during the course of this research, but were not included in the thesis:

Dooley, K., Gupta, J., Patwardhan, P. (2018) INEA editorial: Achieving 1.5 C and climate justice. *International Environmental Agreements: Politics, Law and Economics*, 18:1–9.

Dooley, K. (2018) Human rights and land-based carbon mitigation, in: Dyucks, S., Jodoin, S., Johl, A. (eds) *Routledge Handbook of Human Rights and Climate Governance*, Routledge.

Dooley, K., & Parihar, G. (2017) Human rights and equity as governing values for the international climate regime, in: Cadman, T., Sampford, C., and Maguire, R. (eds) *Governing the Climate Regime: Institutional Integrity and Integrity Systems*, Routledge.

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A big thankyou to my family – to my mum for her continuous support, and to Meaghan and Nathan, who have graciously hosted me on my many and frequent visits to Melbourne over the course of the past 4 years while completing this work. A special thanks to little Ike, who was born, reminding us all why the future is so important. Finally, thank you to Pete, without whose love and support over the final months of this work, I may never have completed.

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Abbreviations

BECCS	Bioenergy with Carbon Capture and Storage
CBDR	Common but Differentiated Responsibilities
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
GHG	Greenhouse Gas Emissions
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
IR	International Relations
KP	Kyoto Protocol
LULUCF	Land-use, Land-use Change, and Forestry
NETs	Negative Emissions Technologies'
NPP	Net Primary Production
PA	Paris Agreement
REDD+	Reduced Emissions from Deforestation and Forest Degradation
SDGs	Sustainable Development Goals
SSPs	Shared Socio-economic Pathways
STS	Science and Technology Studies
UNFCCC	United Nations Framework Convention on Climate Change

Chapter 1

Introduction

The Intergovernmental Panel on Climate Change (IPCC) acknowledges that climate change mitigation is not merely a technical exercise, but will involve myriad decisions among states and civil society actors (Edenhoffer et al. 2014). The land-use sector is a critical element of a successful global climate strategy, but at the same time there are competing demands for and uses of land. The question then, of the ways in which alternative approaches to land governance can enhance sustainability, and the potential trade-offs between climate mitigation and sustainable development objectives is an important one to answer.

In this thesis, I approach the inclusion of the land-sector in the international climate regime as an example of how power is exerted through knowledge and politics in that regime. I investigate to what extent the knowledge-power nexus at work in the climate regime is attentive to the different stakeholders, land users and land-uses, and the different ways of knowing that are relevant to land sector governance. Such practices raise questions about the roles of expertise, transparency and accountability in decision-making, and how a 'technocratic' (expert-led) approach to climate governance reflects power relations in policy development, with often unexamined distributional consequences. The use of (carbon-cycle) science to inform the role of the land sector as a climate mitigation strategy warrants further investigation, given that in practice, policies to reduce emissions from land use have direct consequences for a large proportion of the global poor, who are reliant on subsistence agriculture and forest areas for daily needs.

Emissions from land-use change (largely deforestation and agriculture) contribute roughly a quarter of global greenhouse gas (GHG) emissions, and are therefore an important part of the ongoing United Nations Framework Convention on Climate Change (UNFCCC) negotiations. The land-use sector was initially included in the Convention as LULUCF (land use, land-use change and forestry), and applied only to

developed countries with mitigation commitments under the Kyoto Protocol. Negotiations subsequently began to seek ways to provide policy incentives for developing countries to reduce emissions from deforestation and forest degradation, which saw a shift in focus from technical accounting rules, to consideration of broader issues including rights, livelihoods, and biodiversity protection. The need to address emissions from deforestation in developing countries saw an international agreement on a policy mechanism for reducing emissions from deforestation and forest degradation (REDD+), concluded in 2012 under the UNFCCC. Subsequent negotiations, in the lead-up to a post-2020 climate agreement, raised questions of how land-use would be integrated into a mitigation framework to include developed and developing countries.

The adoption of the Paris Agreement in December 2015 left aside the technical questions around integrating LULUCF and REDD+ into a new climate framework, but instead placed land-based mitigation front and center. The bottom-up approach of the Paris Agreement has changed the terms of inclusion of the land-sector from the more restrictive Kyoto Protocol. Elements of the Agreement's long-term mitigation objective raise the possibility of unprecedented reliance on land-based mitigation. The Paris Agreement commits the international community to "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels (United Nations 2015, Article 2.1a) while the long-term objective of the Agreement calls for "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases… in the context of sustainable development and efforts to eradicate poverty" (United Nations 2015, Article 4.1).

The degree to which such a balance is achievable, and the potential trade-offs, risks and opportunities of this approach in relation to sustainable development objectives, are the focus of this thesis.

1.1 Climate change and the problem of land-based mitigation

Land-use in the climate convention

The inclusion of land-use in the international climate regime was contentious from the start. Some saw this as a way to weaken commitments to reduce GHG emissions from industrial sources, while others believed inclusion of the land sector was integral to combating climate change (Schlamadinger et al. 2007; Schlamadinger & Bird 2007). The technical debates that have occurred around the inclusion of LULUCF in the Kyoto Protocol, REDD+ for developing countries, and now the reliance of the Paris Agreement on 'removals by sinks', underscores the continuing challenges to including the land-sector in the climate regime.

Including terrestrial emissions in the same accounting framework as emissions from fossil fuel use, as occurred in the Kyoto Protocol, creates considerable accounting complexities. This complexity is due to the unique nature of the land-use sector, which is the only sector where CO_2 is sequestered (via photosynthesis), as well as emitted (via forest burning and clearing and land-use change for agriculture, among other activities). It is the inclusion of biological sinks (sequestering CO_2) with biological and industrial sources (emitting CO_2) in the same accounting framework that increases accounting complexities and enhances the risk of using natural sinks to offset anthropogenic emissions. Yet mitigation policies in the land-use sector (involving reduced deforestation, improved agricultural practices and land-use change) must also consider development and food security needs, especially given that more than half of emissions from many developing countries originate from land-use and are bound to these two imperatives.

Resolving the complexity of including terrestrial and industrial emissions in the same accounting framework resulted in negotiations of such technical sophistication that all but a limited group of experts were excluded. While much of the literature covering the inclusion of LULUCF in the climate regime emphasizes the technical rationales underpinning the development of accounting rules (Höhne et al. 2007; Schlamadinger et al. 2007), a body of literature points to the political contestation underlying these decisions (Fry 2002; Lövbrand 2009; Fogel 2005; Fry 2007; Lövbrand 2004). From a technical point of

view the key concern was that, in the absence of limits, the scale of land sector emissions and removals could outweigh efforts to reduce industrial emissions (Höhne et al. 2007). Political analysis on the topic however, raised questions around the technicalization of negotiations on accounting rules, the selective use of 'sequestration science' for political ends, and the distributional outcomes of these practices (Lövbrand 2004; Fogel 2005). Ultimately, the inclusion of land use in the Kyoto Protocol was a compromise between opposing political views (Lövbrand 2009), but the scene was set for an expert-led , or technocratic, approach to the role of the land sector in global climate governance.

'Negative emissions' raise critical questions

With the international community's commitment to the Paris Agreement, the need to remove carbon from the atmosphere has become central to the climate policy agenda. In 2016, global atmospheric CO_2 concentration averaged 402.8 ppm, an increase from ≈277 ppm in 1750 (Le Quéré et al. 2018). To achieve the 'deep mitigation scenarios' required for the 2 °C and 1.5 °C goals of the Paris Agreement, atmospheric CO_2 concentrations must be below 450 ppm and 430 ppm respectively (IPCC 2013, 2014). One result of the focus on deep mitigation scenarios is that 'negative emissions technologies' (NETs), referring to the removal of carbon dioxide from the atmosphere, have increasingly appeared - explicitly or implicitly - in analyses and discussions of options for addressing climate change on a truly massive scale (Anderson 2015a, Fuss et al. 2014). In almost all of the modelled pathways for 2 °C and 1.5 °C, two to three times the amount of the available global carbon budget is emitted, with the excess atmospheric carbon (up to 1200 Gt CO_2) projected to be removed through negative emissions over the course of the century (Riahi et al. 2017; Rogelj et al. 2018).

While a variety of negative emissions options have been discussed in the literature (Williamson 2016; Minx et al. 2018), modelled mitigation scenarios universally assume that negative emissions will be achieved through land-based options - reforestation and bioenergy with carbon capture and storage (BECCS) - measures that require appropriating extensive areas of land to this end (c.f. Popp et al. 2017; Rogelj et al. 2018). This raises questions regarding the feasibility of large-scale land-based carbon removal, given the

potential impacts of increased land demand on sustainable development objectives (Williamson 2016; Vaughan & Gough 2016; Smith et al. 2015). This scale of reliance on land-based mitigation (potentially requiring a land-area the size of the Australian continent (c.f. Rogelj et al. 2018)), could reduce the availability of productive agricultural land, and encroach on natural land. The social and environmental implications of such measures have not yet been fully assessed (Buck 2016; Vaughan & Gough 2016; Fuss et al. 2018).

The Paris Agreement sets no limits on 'balancing' emissions with removals. If removals via terrestrial sinks are expected to make a significant contribution to achieving the long-term mitigation goal, this implies a need for land to shift, eventually, from being a net source of emissions globally to a net sink. The distributional consequences of this shift in land-use are crucial: the IPCC states that models ''universally project that the majority of agriculture and forestry mitigation, and bioenergy primary energy, will occur in developing and transitional economies'' (Smith et al. 2014). Large-scale changes in land-use, including increased reliance on terrestrial carbon sequestration for mitigation or biomass for energy, "result in competition for land (and sometimes other resources such as water) that may have substantial social, economic, and ecological effects" (Smith et al. 2014). Achieving the 'balance' in the context of sustainable development, also part of the mitigation objective of the Paris Agreement, will be critical for successful land mitigation.

The politics of expertise

The role of experts in public decision making has attracted scholarly attention, particularly concerning environmental issues, given the highly technical nature of these problems. Scholars have raised questions over the democratic accountability of experts, an absence of which has the potential to undermine trust in experts (Backstrand 2004; Fischer 2009; Jasanoff 2003; Jasanoff 2006; Sarewitz 2004; Weingart 1999). Fischer, for example, has written extensively on technocratic versus democratic approaches to governance, and that scientific expertise is not the neutral objective phenomenon it has long purported to be (2009). Yet the neutrality of science is called into question when a lack of interrogation of the nature of expertise in the

policy making process conceals important power dynamics (Jasanoff 2004d). Jasanoff has observed that the "technocratic vision of public policy has scored important gains over the competing democratic paradigm", as scientific advice has become an integral part of public decision making (1990a, p.229). Stevenson (2013) notes that seeing climate change as a technical problem overlooks its social and political dimensions. Other analysts contend that environmental science narratives are used to "project an illusion of natural resources that require better management and enhanced legislation to ensure that poor people benefit, while overlooking highly political struggles over environmental control and rights to resources" (Waldman 2005, p. vii, see also Ferguson 1994; Easterly 2014).

In terms of who determines climate policy and how, Backstrand and Lövbrand (2015) refer to the 'politics of expertise' where close links between knowledge-making authority and decision-making authority advantage those with greater access to knowledge resources. Translation of such knowledge into institutional forms can result in an expert-led (technocratic) approach to global climate governance. Stevenson argues that the normative shift towards a technical focus in international climate negotiations has meant global climate governance has become a task of "mitigating emissions at cheapest source, rather than transforming political, economic and cultural drivers of excessive emissions" (2013, p.4). This focus on 'least cost solutions' has pushed mitigation in the land-use sector into a prominent position, garnering political attention and momentum disproportionate to the abatement potential of the sector, according to some scientists (Haberl et al. 2012; Mackey et al. 2013; Powlson et al. 2011).

The focus on least cost solutions can also be seen as a major contributor to current expectations for large-scale reliance on land-based negative emissions to achieve deep mitigation scenarios. In the idealized world of cost-optimization models, the inclusion of negative emissions buys time, allowing societies to avoid near-term mitigation costs by relying on options that are deferred to the future. Yet relying on future reversal of today's emissions poses risks that may substantially undermine society's overall mitigation efforts. In a world committed to limiting climate change to well below 2 °C, reliance on negative emissions allows greater continued use of fossil fuels, and shifts the mitigation burden to future generations, raising the question of moral hazard (EASAC 2018, Muratori et al. 2016).

Knowledge production is marked by moments of problematization and crisis during which conflicts and new epistemologies (theories of knowledge) arise (Winkel 2012; Whatmore 2009; Jasanoff 2004b). This epistemological struggle has been well documented in the context of inclusion of the land sector in the Kyoto Protocol, and the same trend can be seen with rapid growth in critiques (and counter-critiques) of assumed reliance on negative emissions in climate models (Anderson & Peters 2016; Knutti 2018; van Vuuren et al. 2017; Carlsen et al. 2017; Beck & Mahony 2017). Publications in critical social theory (Fogel 2005; Backstrand & Lövbrand 2006; Gupta et al. 2012; Lövbrand 2009) argue that accounting systems grant international experts a key role in terrestrial carbon governance. Lövbrand (2009) in particular has explored in detail what she terms the links between knowledge-making and decision-making authority in multilateral climate negotiations on terrestrial sources and sinks of greenhouse gases. However, to date, there is little critical social analysis of the impacts of expanding the role of biological sinks to meet the objectives of the Paris Agreement, while also meeting sustainable development objectives.

1.2 Rationale

Balancing emissions from sources and removals by sinks is central to the long-term goal of the Paris Agreement, which states that the 'balancing' must be done ''on the basis of equity,'' and ''in the context of sustainable development and poverty eradication'' (United Nations 2015 Article 4.1). A key dilemma is thus how to secure land-based mitigation so as to enhance collective climate action, without undermining equity and sustainable development objectives. Previous analysis has shown that the acknowledgement of the importance of equity and sustainable development in the international climate regime does not automatically translate into more sustainable solutions (Stevenson 2013). In fact, Stevenson asserts that a technical approach to governance has resulted in "state actors pursing compliance with the climate regime in ways that reinforce and further institutionalize unsustainability" (2013, p.60).

Land-use accounting rules can be seen as an example of a technocratic approach, with 'sequestration science' selectively evoked or rejected to create rules that suit the specific circumstances of each state (Lövbrand 2007). A similar problem can be seen with the Paris Agreement, where the 'balance' language

creates a reliance on carbon-dioxide removal, which in turn is expected to be met with an increase in biological sinks. Yet, while the second half of the Paris Agreement's mitigation objective requires sustainable development objectives to be met, proposals for large-scale reliance on land-based mitigation pose clear and significant risks to sustainable development. At the same time, there is unexplored potential for synergies between climate mitigation in the land sector and the achievement of the 2020 sustainable development goals (SDGs). The SDGs represent a consensus set of global objectives related to development, and it is inevitable that increased demands for land from climate mitigation will affect their attainment. It is therefore important to assess the potential for enhanced sinks not just from a technical perspective, but in terms of trade-offs and synergies with SDGs, many of which are reliant on land.

Arising from the above analysis of technocratic governance approaches, this thesis is concerned with how the capacity to meet sustainable development objectives can be preserved while also allowing for successful land sector mitigation. The specific aim is to examine how land can play a central role in deep mitigation scenarios, while also contributing to related sustainable development objectives, and to explore in what ways the use of climate science constructs and enables, or conversely undermines, these twin objectives.

To do this I focus on three distinct but inter-related and also sequential issues: first, I consider the politics inherent in the development of land sector accounting rules. Second, I analyze the co-production of science and climate policy in the context of modelled mitigation scenarios compatible with the Paris Agreement. Finally, I examine the potential impacts of land-based mitigation measures on those SDGs reliant on land - in particular for food security and biodiversity objectives.

When referring to land-based mitigation, the scope of this thesis is limited to carbon-related terrestrial emissions, i.e., CO_2 emissions and removals from forests, soil carbon, and cropping and grazing activities (as defined by current IPCC reporting guidelines on LULUCF activities) (IPCC 2006). This excludes consideration of non-CO_2 agricultural activities (such as livestock management and fertilizer use), which are the dominant sources of emissions from the agricultural sector. The focus of analysis is on the international climate regime (the UNFCCC), incorporating also the IPCC in its scientific advisory role to

the UNFCCC, as the most appropriate multilateral institution to address the governance of large-scale carbon removal.

1.3 Research Questions

In light of the above rationale, the core question of this thesis is to ask in what ways does the use of climate science construct and enable land-based mitigation to meet the 'balance' objective of the Paris Agreement, and is this compatible with the Agreements 'sustainable development' objective?

In order to examine the critical issues for land sector mitigation, and the role of knowledge and power in constructing policy outcomes, this thesis will address the following subsidiary research questions:

1. How is terrestrial carbon science co-produced with policy demands in the context of land-use in current and future mitigation pathways?

2. How have land-based negative emissions been legitimized as key mitigation options under the Paris Agreement?

3. What are the outcomes of a technocratic approach to terrestrial carbon mitigation, and what are the potential implications for sustainable development objectives?

The ultimate aim of asking these questions is to evaluate the normative outcomes of global climate governance (governance implications) in the context of land-based mitigation. The question of how land can play a key role in deep mitigation pathways, while ensuring that the objectives of equity and sustainable development in the international climate regime are not undermined, will rely heavily on governance of land resources, at scales of global and local governance.

1.4 Significance of the study

This thesis addresses a number of gaps in the scholarly literature. First, the thesis places findings from examining the power-knowledge relationships at play in past and present international negotiations on land-use in climate mitigation in the context of future projected land-use mitigation pathways, which is an area not tackled in current literature. The majority of existing literature on this topic is focused on the historical period pertaining to land-use in the Kyoto Protocol negotiations, but does not look at how this has framed the treatment of the land sector in the Paris Agreement, and the future governance implications. Using land as the common thread, this thesis examines the politics of expertise in the disproportionate role of land-based mitigation in global climate governance.

Second, this research will make an important contribution to social analyses of terrestrial carbon mitigation, relevant in international negotiations as well as domestic policy settings, at a time when many governments are pushing to expand the currently limited role of land sector mitigation in climate abatement to a much more critical role.

The politicization of science is well documented, and "although pleas for separation of science and policy continue, the artificiality of this position can no longer be doubted" (Jasanoff 1990, p.230). Yet this understanding does not translate into much of the policy debate around climate change where objective scientific input and separation between science and values is still sought, as can be seen in the mandate of the IPCC to be: "policy relevant, but not policy prescriptive" (IPCC 2013, p.1). Applying established critical theories to current policy debates on the role of land-based mitigation in future climate mitigation pathways offers a chance to 'repoliticize', and bring to the fore important conversations about the trade-offs inherent in relying in land for climate mitigation. This can strengthen and build trust in expert input into policy debates, when it is recognized that a "powerful role for science in society is to facilitate the creation of… new policy alternatives" (Pielke 2007, p.9).

1.5 Thesis overview

The rest of the thesis proceeds as follows: Chapter 2 provides a background discussion of the terrestrial carbon cycle, in order to understand the various options for land-based mitigation, the trade-offs inherent in these, and the scientific controversies that still surround avoiding or enhancing terrestrial carbon fluxes. This background understanding is necessary in order to interrogate the technical debates around land-based mitigation. Chapter 3 then introduces a conceptual framework for the thesis based on an understanding of the multiple conceptions of power at play in international politics (Barnett & Duvall 2005), and on science and technology studies, focusing in particular on the concept of the co-production of science and society (Jasanoff 2004c).

The body of the thesis then examines the history, the current epistemic battles, and the potential future risks, in land-based climate mitigation under the international climate regime. An historical analysis of the contested process of negotiating politically palatable (but also scientifically defensible) accounting rules for land-based mitigation is provided in Chapter 4. This chapter concludes with an assessment of how these historical trends may or may not be institutionalized in the new post 2020 climate agreement (Dooley & Gupta 2017). Chapter 5 then considers the current epistemic battle around future climate mitigation pathways as proposed by integrated assessment models, and the scale of land-based climate mitigation inherent in these. Taking co-production as an analytical lens, this chapter interrogates how policy demand for deep mitigation scenarios has resulted in proposed future development pathways that raise significant concerns regarding social and environmental impacts (Dooley et al. 2018).

In Chapter 6, I argue that extending the near-term carbon budget by presupposing the future availability of negative emissions poses risks that are of a different nature than those posed by conventional mitigation options. Accepting these risks may lock us into much higher levels of future warming than intended, and/or force us to confront considerably higher social and ecological costs. Based on the findings from previous chapters that see political questions obscured in technical approaches to climate policy, this chapter takes on the task of applying a normative framework based on the Paris Agreement objectives, to determine the

options for negative emissions that are most synergistic with sustainable development (Dooley & Kartha 2018).

Finally, Chapter 7 draws out conclusions in relation to the research questions and provides a synthesis of the three separately published chapters. This chapter concludes with an overall recommendation that an awareness of the politics of expertise inherent in science-for-policy can inform a more critical examination of the outcomes of climate governance.

Chapter 2

Literature Review

This chapter reviews literature, from both the natural and the social sciences, that informs the following research chapters. This spans literature relating to the terrestrial carbon cycle and technical issues underpinning land-based mitigation; to literature on land availability and the demand for land; to literature on the politics of land use in the UNFCCC. In doing so, I take a cross-disciplinary approach in order to provide insight into the science and the politics that shape and contribute to the various debates around land-based mitigation.

It is important to note that Chapters 4-6 also include short reviews of the most relevant literature within the published papers in those chapters. This includes a review of land-use accounting rules in Chapter 4; a review of critical analysis of climate modelling in Chapter 5; and a review of ecosystem restoration and bioenergy supply potential in Chapter 6. More recent literature that was published after the publication of chapters 4-6 has been added to this Chapter's literature review, to individual chapters, or to the discussion in Chapter 7 as appropriate.

This chapter is divided into three main sections. Section 2.1 starts by providing a background on the terrestrial carbon cycle, which is important to understand when later on I examine the politics of 'sequestration science'. I then review the literature on the potential for various land-based mitigation options, in order to understand current potential and research gaps. Section 2.2 looks at the global availability of, and demand for, land. Several issues are covered here that are important to understand in the context of thinking about land-based climate mitigation – what is the global availability of land for mitigation?; what are the competing demands for land?; and what is the extent of uncertainty around these land estimates? Section 2.3 gives a brief overview of the inclusion of land in the international climate regime, reviewing existing literature on the politics of

how land was included in the UNFCCC. A final section summarizes key themes found in the literature and identifies research gaps. The next chapter, Chapter 3 will build on these findings by developing the overall research design to address the research gaps identified here.

2.1 Land-based climate mitigation

This section aims to evaluate the potential for land-based mitigation, through an understanding of the terrestrial carbon cycle and the sequestration potential in forests and other landscapes, in order to base the critical analyses in subsequent chapters on an informed understanding of the terrestrial carbon fluxes and the dominant land management options.

2.1.1 Terrestrial carbon cycle

Climate change is caused by anthropogenic GHG emissions which have accumulated in the atmosphere since the beginning of the industrial era, which saw the first discernable anthropogenic CO_2 pulses to the atmosphere, initially from land clearing (Ciais et al. 2013; in Le Quéré et al. 2018). Emissions from fossil fuels became the dominant source of anthropogenic emissions from the 1920s, and have continued to increase until the present (Le Quéré et al. 2018). Anthropogenic emissions are redistributed from the atmosphere to the terrestrial and ocean sinks as part of the carbon cycle. Understanding the carbon cycle has important implications for climate policy. Some 600 ±65 Gt C has accumulated in the atmosphere since the start of the industrial era (from 1750 to 2016). Of this, industrial emissions (fossil fuel and cement production) contributed 420 ±20 Gt C and forest clearing and other land-use contributed 180 ±60 Gt C (Le Quéré et al. 2018).

This means 30% of emissions currently in the atmosphere are from land-use change - what has been referred to as the 'land-carbon debt' (Mackey et al. 2013), or the 'loss of sink capacity' (Le Quéré et al. 2018). This is calculated as the difference between the "actual land sink under changing land cover and the counterfactual land sink under pre-industrial land cover" (Le Quéré et al. 2018, p.423), and represents the maximum amount that can be sequestered and returned to the biosphere,

estimated at between 119-187 Gt C (Mackey et al. 2013; Houghton & Nassikas 2017; Arneth et al. 2017).

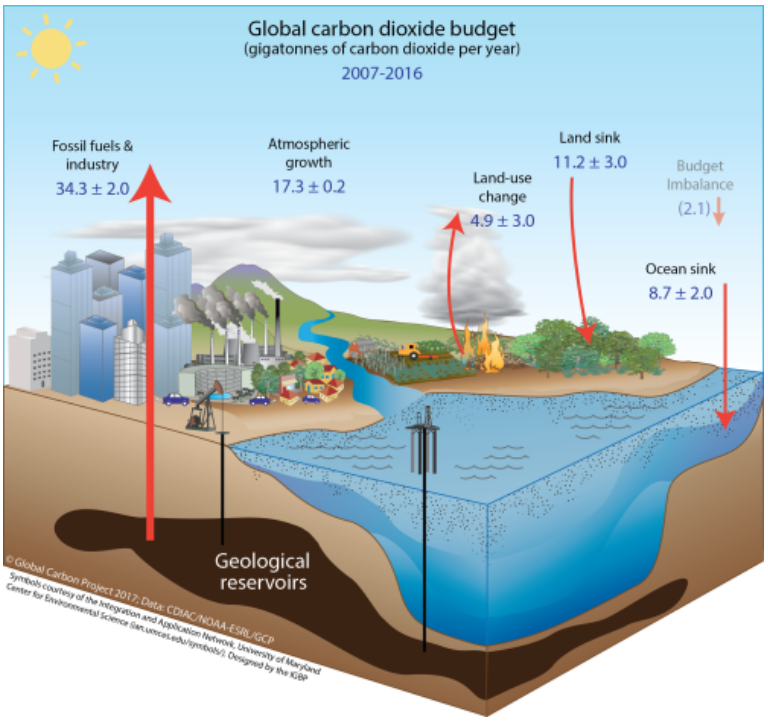

Figure 2.1: Perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2007–2016 (Gt CO_2/yr).
Source: Global Carbon Project

Figure 2.1 shows the annual global carbon cycle, with the major sources of CO_2 emissions depicted as red arrows, and the major sinks as green arrows. (Note that a sink or a source is a flow, it depicts changes over time. A stock of carbon, also called a pool or a reservoir, is static). Fossil fuels and industry represent the major source of CO_2 emissions, which are released when carbon is extracted from geological reservoirs and burnt, increasing the amount of carbon in all parts of the carbon cycle (land, ocean and atmospheric carbon pools). Additional sources of CO_2 come from land-use change - clearing or burning existing vegetation, usually to make way for agriculture or urban expansion.

When considering all GHG emissions, not only CO_2, the land sector (agriculture and land-use change) is considered to be responsible for just under a quarter (approximately 10-12 Gt CO_2 eq/yr) of global annual emissions, mainly agricultural GHG emissions from livestock, soil and nutrient management, and CO_2 emissions from deforestation (land-use and land-use change) (Smith et al. 2014). Of this 10-12 Gt CO_2 eq/yr, net global emissions from land-use and land-use change activities (deforestation, afforestation, subsistence agriculture, forest fires) have remained relatively constant over the past half-century, at approximately 4.3-5.5 Gt CO_2 eq /yr, or 9-11% of total anthropogenic GHG emissions annually (Smith et al. 2014). This figure is the sum of emissions and removals attributable to human activities (Figure 2.2).

Globally, land ecosystems remove about 3.0 ± 8 Gt CO_2 /yr, which is 28% of annual anthropogenic CO_2 emissions through natural processes (photosynthesis) (Le Quéré et al. 2018). This process is known as the residual land sink, which together with the ocean sink removes approximately half of all anthropogenic emissions (Le Quéré et al. 2018). The residual land sink is calculated separately from anthropogenic emissions and removals, although system boundaries make attribution between anthropogenic sinks and the land sink difficult (Erb et al. 2013).

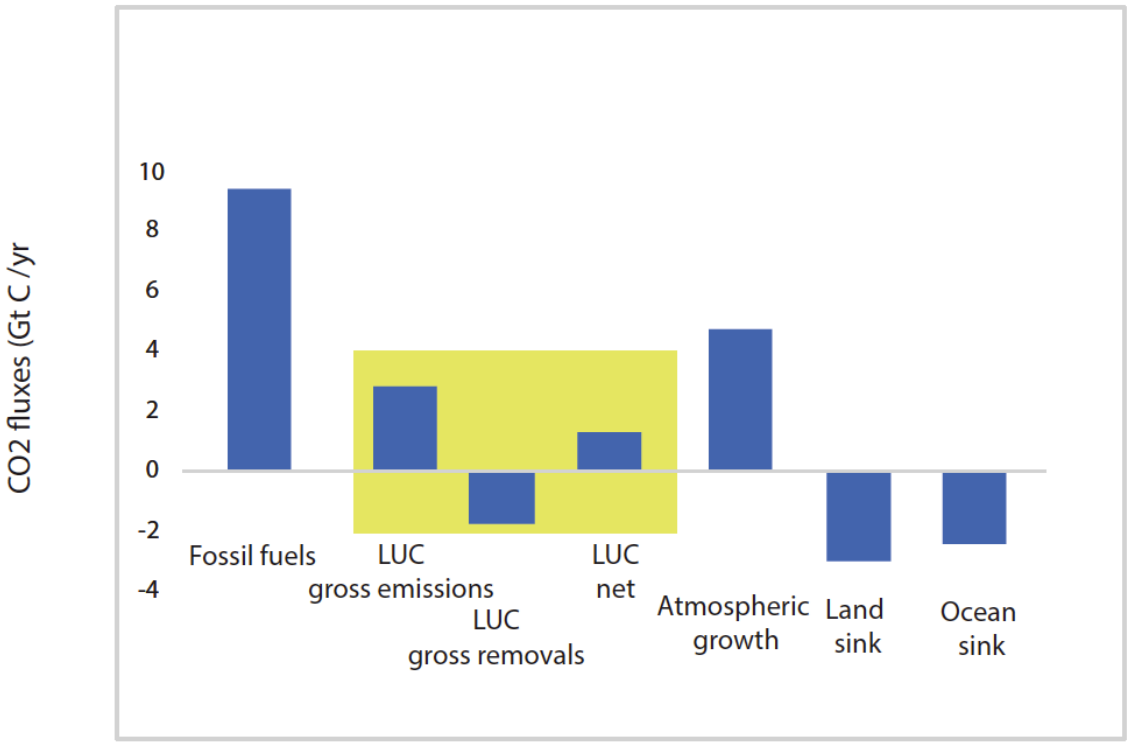

Figure 2.2: Land-use change sinks and sources
Land-use change (LUC) fluxes comprise gross emissions and gross removals, leaving a net LUC source of 1.3 Gt C/yr from human activities in the land sector. LUC net emissions, as well as fossil fuel emissions, contribute to atmospheric growth, which is taken up by the land and ocean sinks. Source: adapted from Canadell and Schulze 2014, with data from Le Quere 2018.

The residual land sink has almost doubled since the 1960s, in response to increasing atmospheric CO_2, which 'forces' more uptake by the land and ocean sinks (Le Quéré et al. 2018). While a majority of climate models project a continued net carbon uptake by the land sink, some models show a net CO_2 source to the atmosphere from land due to the effects of climate change causing sink weakening (IPCC 2013). Models of the global carbon cycle to 2100 consistently report a positive feedback between climate change and the terrestrial carbon cycle - decreased sinks and increased terrestrial emissions (IPCC 2013, 2014). In other words, climate change puts the mitigation benefits of biological sinks at risk, and recent research continues to point to evidence of a declining land sink (Curran & Curran 2016a; Curran & Curran 2016b; Raupach et al. 2014; Nabuurs et al. 2013). However, the most recent global carbon budget update from Le Quéré et al.,

(2018) concludes that given significant inter-annual and decadal variability in the land sink, there is currently no firm evidence of sink weakening.

2.1.2 Land-based carbon removal options

Assessments for land-based mitigation, such as those included in the Fourth and the Fifth Assessment Reports from the IPCC (Smith et al. 2014), rely on strong abatement potential from bioenergy and soil carbon sequestration, which some have claimed is overestimated (Haberl et al. 2012; Powlson et al. 2011). With the advent of the Paris Agreement, the focus has shifted to removal of carbon dioxide from the atmosphere (also known as negative-emissions), with modelled mitigation pathways focusing on carbon sequestration – the ability to remove carbon from the atmosphere via photosynthesis. Modelled IPCC scenarios for limiting warming to below 2 °C and 1.5 °C almost universally rely on large scale bioenergy with carbon capture and storage (BECCS) to remove carbon from the atmosphere, as well as forest plantations (Anderson 2015a; Williamson 2016). The inclusion of BECCS in modelled scenarios compatible with the Paris Agreement has drawn increasing criticism over negative social and environmental impacts (Williamson 2016; Smith et al. 2015; Vaughan & Gough 2016; Boysen, Lucht & Gerten 2017; Heck et al. 2018), but has also launched a stream of literature on scaling up and innovation of 'negative emissions technologies', which as has recently been drawn together in a three-part, comprehensive review (see Minx et al. 2017; Fuss et al. 2018; Nemet et al. 2018). Perhaps most notably, a technical report from the Convention on Biological Diversity (CBD) has concluded that the land-use change envisaged in IPCC scenarios for below 2 °C would lead to "large losses of terrestrial biodiversity" (Williamson & Bodle 2016, p.18).

In the following section I briefly assess the potential for carbon dioxide removal from the land sector, covering forests (managed and natural), bioenergy, degraded lands, and soil carbon. I evaluate the potential sequestration magnitude of these options, as well as associated social or environmental impacts, based on the current literature.

Forest sequestration potential

Forests cover a broad range of management practices, forests biomes, and ecosystem types, with accordingly different productivity rates, management, and restoration potentials. Proposals for large-scale forest plantations to sequester carbon have met with critiques similar to those for BECCS, as outlined above, again for reasons of land demand and nutrient input (Smith & Torn 2013; Smith et al. 2015; Field & Mach 2017). Alternatives are however being put forward to large-scale plantations, from changed management practices, to the restoration of degraded forests and other ecosystems.

Until the mid-twentieth century, the major losses of terrestrial carbon were from non-tropical regions (North America, Europe, Russia, Australia), as a result of wood harvesting and agricultural expansion (Houghton et al. 2012). It is only since the 1950s that deforestation for agricultural expansion was predominantly in tropical regions (Houghton et al. 2012). The mitigation potential from forest restoration therefore exists across all forest areas which have historically been depleted, and is not confined to the tropics.

Forests cover one-third of the earth's land area, which can be divided into biomes, each representing a distinct ecological region (Pan et al. 2011). Forest biomes are most broadly divided into tropical, temperate and boreal forests, although there are further subdivisions, particularly among evergreen and deciduous forest types, and humid and semi-arid zones (Pan et al. 2011). Of the tropical forest area 70%, or 1392 million hectares (Mha), represents intact tropical forests, while regrowth forests represent ~30% (557 Mha) (Pan et al. 2011). Table 2.1 shows how carbon stocks differ across forest biomes for the total forest carbon stock, as well as the five forest carbon pools. There are significant differences in the way carbon is stored across the different forest biomes, which impacts on the potential to enhance sequestration. Boreal forests store carbon mostly in soils, while in tropical forests carbon is stored mostly in the living biomass (above and below ground). Temperate forest biomes have a high carbon sink capacity and can have carbon densities as high as tropical

forests (Lal & Lorenz 2012), with the world's highest known total biomass carbon density occurring in Australian temperate moist forest (Keith et al. 2009). Estimates suggest the sum of above- and below-ground carbon within tropical forests is greater than 500 Gt C, about half the estimates of the carbon within fossil fuel reserves (Houghton et al. 2015). This volume of forest carbon stock, and the extent of secondary or degraded forest, highlights the significant mitigation potential in restoring carbon to the biosphere.

	Global forests		*Tropical*		*Boreal*		*Temperate*	
	Gt C	%	Gt C	%	Gt C	%	Gt C	%
Total forest carbon stocks	861 ± 66	100	471 ± 93	55	272 ± 23	32	119 ± 6	14
Soil (to 1-m depth)	383 ± 30	44	213*		338*		153*	
Live biomass (above and below ground)	363 ± 28	42						
Deadwood	73 ± 6	8						
Litter	43 ± 3	5						

Table 2.1: Global forest carbon stocks, divided by biome and carbon pool

**Forest soil carbon for biomes are from Lal et al 2012, which gives different forest carbon figures than Pan et al 2011, hence the global total for forest soil carbon does not correspond with biome-based soil carbon. Another source (Bhatti 2012) gives different numbers again, estimating the total boreal forest stores at 715.2 Gt C, with 430.2 Gt C present in peatlands (soil) and the remaining in forest carbon stocks. Source: Compiled from Pan et al, 2011; Lal et al 2012; Bhatti 2012.*

Globally, boreal and temperate forests are net carbon sinks that have been increasing in strength over recent decades, while tropical forests have remained a net source (Table 2.2). However global data can hide regional variations - the relatively stable boreal carbon sink is the sum of a net reduction in the Canadian biomass sink offset by increases in all other boreal regions (Pan et al. 2011). Emissions from tropical forests are mostly from land clearing through deforestation and forest degradation, and the burning and draining of peatlands. Including emissions from drained peatlands brings the net emissions from land-use change to 1.3 Gt C/yr (Le Quéré et al. 2018). However, a newly published map of tropical peatlands suggests a greater extent and depth of

tropical peat than were previously reported (Murdiyarso et al. 2017). This suggests new priorities for the conservation of high-carbon value peatlands, with South America having greater extent of peat than previously reported, and Brazil rather than Indonesia now mapped as the world's largest area of tropical peatlands.

	Sink (Gt C/year)	*Source (Gt C/year)*	*Net flux (Gt C/year)*
Tropical	- 1.7 ± 0.5	+ 2.8 ± 0.4	+ 1.1 ± 0.1
Temperate			- 0.7 ± 0.9
Boreal			- 0.5 ± 0.08
Global forests (inc. peat)	- 1.8 ± 0.5	+ 2.8 ± 0.5	+ 1.3 ± 0.1

Table 2.2: Gross and net anthropogenic carbon flux from forest biomes

Source: Tropical figures from Pan et al, 2011. Global gross figures from Canadell and Schulze 2014; Global net figures from Le Quéré et al, 2018. The tropical forest sink declined from 1.5 Gt C /yr in the 1990s to 1.1 Gt C /yr for 2000 to 2007. There remains a substantial lack of data for areas of the boreal forest in North America, including Alaska (51 Mha) and Canadian unmanaged forests (118 Mha), and a notable lack of data on extent of degradation and regrowth rates of tropical forests worldwide (Pan et al., 2011).

In many forest biomes, recovery of degraded forest lands could yield substantial carbon benefits. However, the rates at which biomass recovers in degraded lands are variable and the extent of degraded lands is largely unquantified (c.f. Gibbs & Salmon 2015 as well as section 2.3). Degraded ecosystems recover naturally over time; ecosystem restoration can be defined as enabling or accelerating that recovery. In the case of forests, some areas can recover unaided if protected from further disturbance. Other ecosystems, particularly dryland and mixed use agricultural areas, may require planting and other interventions for recovery (Lamb et al. 2005). Potentially higher sequestration rates can be achieved through restoring degraded natural forests than through forest plantations (due to higher carbon densities of natural forests) meaning less land is needed for the restoration of degraded forests (Houghton et al. 2015).

While humid tropical forests are a net source of emissions, the figures reveal a high rate of turnover: the carbon sequestration in intact and recovering forests is almost equal to the net emissions from forest loss (Venter et al. 2012). This means that small reductions in forest loss or increases in forest sequestration could tip the balance, making humid topical forests part of the solution for climate change (a net sink) instead of a source of emissions (Venter et al. 2012). Houghton et al. (2015) suggest that tropical forest management could play a critical role in keeping temperatures well below 2 °C, putting the potential mitigation contribution of tropical forests at 5 Gt C/yr. This estimate is based on 1 Gt C/yr of avoided emissions through halting forest conversion; 3 Gt C/yr of removals through allowing all harvested forests and the fallows of shifting cultivation to regrow; and a further 1 Gt C/yr in removals through the re-establishment of forests on 500 Mha of previously forested lands not in productive use (Houghton et al. 2015). This 4 Gt C/yr sink would last for around 50 years before declining linearly to zero, meaning that removing carbon from the atmosphere through tropical forest regrowth is a one-off mitigation opportunity, and is based on the assumption that the land sink will not weaken. A more recent update from Houghton and Nassikas (2017) puts the tropical forest sequestration potential at 3.3 Gt C/yr, without any area of reforestation, while Griscom et al. (2017) estimate 2.75 Gt C/yr sequestration potential from reforestation in temperate and tropical biomes.

However, while the most recent and accelerated forest loss has been in tropical forests, there has been little change or re-carbonization in developed countries forests in the temperate zone and boreal regions (Houghton, 2012). Other studies assessing the climate mitigation potential of temperate and boreal forest biomes suggest much smaller, but still significant, sequestration potential for these forests. Various studies focused on temperate forests in the European Union suggest changing management regimes (restoration, reduced harvest and protected areas) could result in an average carbon sequestration of 56.3 Mt CO_2 /yr in Germany's forests (Böttcher 2018); or up to 441 Mt CO_2 /yr in sequestration above the historical baseline across all forest areas in the European Union (Nabuurs et al. 2017).

Large areas of boreal forests are allocated to timber production. The key forest management activities here are harvesting and forest fire management, with fire being the most significant cause of forest loss in boreal regions (Bhatti et al. 2012; Hansen et al. 2013). Studies examining increased sink potential in boreal forests are summarized in Table 2.3. All of these assume a combination of better utilization of forest products, reduced harvest and altered management (thinning, etc), but the mitigation gains remain small (Smyth et al. 2014; Lundmark et al. 2014). For boreal forests Bhatti et al. (2012) recommend that reducing the area prone to fire and insect mortality, and extending the rotation age for holding carbon longer in older age classes will strongly increase the carbon sequestration capacity of boreal forests. Achieving this increased sequestration however, will require significantly reduced harvest rates. A recent study focused on 'natural climate solutions' suggests that halting all timber harvest in secondary forests for 50 years would deliver a cost constrained mitigation potential of 1.5 Gt CO_2/yr sequestered across 1914 Mha of secondary forests across all forest biomes (Griscom et al. 2017).

Bioenergy

The expectation for large-scale bioenergy use in the form of BECCS to remove carbon from the atmosphere in modelled mitigation scenarios has reignited debates over the carbon-neutrality of bioenergy (i.e. over whether CO_2 released when biomass is burnt is recaptured in regrowth) and highlighted the uncertainties over the sustainable supply of various biomass feedstocks. Estimates in the literature on global primary bioenergy potential by 2050 "span a range of almost three orders of magnitude, from <50 EJ /year to >1000 EJ /year" (Creutzig et al. 2015, p.917) but have more recently centered on a range of 100-300 Exajoules (EJ) by 2050. The upper end of this range would require a doubling of current human harvest of all global biomass for all uses (food, feed and fibre) (Haberl et al. 2013; Searchinger et al. 2015). Recent assessments point to a consensus that the lower end of this range (100 EJ/yr) could be sustainably supplied (Smith et al. 2014; International Energy Agency 2017), although such projections would be dependent on strong global land governance systems (Creutzig 2017). In comparison, current global bioenergy use is currently

around 55 EJ/yr (including residues and waste), equivalent to around 12% of fossil fuel use (Haberl et al. 2013).

Bioenergy is seen as part of the mitigation portfolio because it is assumed to be carbon neutral - CO_2 is released when bioenergy is combusted but then recaptured when the biomass stock regrows. Such an assumption relies on all of the biomass being replaced through regrowth, given that combustion of biomass for power generation or heating "will generally release more carbon dioxide to the atmosphere per unit of delivered electricity or heat than fossil fuels, owing to biomass having lower energy density and conversion efficiency CO_2 emissions per unit of energy produced" (EASAC 2018, p.21). Due to peculiarities in Kyoto Protocol accounting rules, a loophole exists that means these emissions from bioenergy go unaccounted for in many countries, where depleted land carbon stocks may not be included in national inventories (Searchinger 2009).

There is a growing scientific consensus that the use of forest products (e.g. woodpellets or roundwood) for bioenergy is not carbon neutral. In 2015 Ter Mikalean et al. published an overview of forest carbon accounting for bioenergy, noting that "misconceptions and errors" in methodologies continue to affect assessments of the effects of bioenergy use on the GHG concentration in the atmosphere "despite having been addressed in prominent publications (e.g., Searchinger et al. 2009, Haberl et al. 2012)" (2015, p.57). Further studies, taking account of alternative harvest scenarios and applying carbon-cycle models, confirm that in all cases an increased harvest level in forests leads to a permanent increase in atmospheric CO_2 concentration (Sterman et al. 2018; Lundmark et al. 2014; Holtsmark 2013; Smyth et al. 2014).

Despite this seemingly robust scientific evidence, some continue to argue that bioenergy is carbon neutral under a 'sustainable harvest' model where all harvest is replaced (see for example studies cited in Holtsmark 2013). These studies are critiqued for ignoring the counterfactual scenario of no forest harvest. When no forest harvest is taken as a baseline scenario, the global warming potential from bioenergy is significantly higher than from fossils fuels over a 100 year time frame

(Holtsmark 2013; Schulze et al. 2012, Ter Mikalean et al. 2015). Prominent studies continue to highlight that increased atmospheric concentrations from the burning of bioenergy may worsen irreversible impacts of climate change before forests eventually grow back to compensate (EASAC 2017; Booth 2018; Schlesinger 2018). Schlesinger (2018) underlines this point: "cutting trees for fuel is antithetical to the important role that forests play as a sink for CO_2 that might otherwise accumulate in the atmosphere".

There is greater agreement that the use of forest residues, rather than harvesting forests for bioenergy, could be carbon neutral. Most recently a letter signed by 800 scientists sent to the European Parliament requested forest biomass eligible under the European Union Renewable Energy Directive to be restricted to forest residues and wastes only (Beddington et al. 2018). However, recent research highlights that burning residues can still release more emissions to the atmosphere in the mid-term (20-40 years) than allowing them to decay, a timescale relevant to climate mitigation efforts (Booth 2018). There is general agreement that specific and limited waste materials from the forest industry (for example black liquor or sawdust) may be used with beneficial climate effects (EASAC 2017).

The use of annual crops for bioenergy presents a different set of issues to consider. Many argue annual crops are carbon-neutral compared to woody bioenergy due to the annual nature of regrowth, meaning that CO_2 released during combustion is recaptured within 12 months, which avoids the long pay-back periods of forest harvest (Creutzig et al. 2015). However, some argue that this again ignores the counter-factual - the existing carbon stocks of the land if not harvested for bioenergy. Most land is part of the terrestrial carbon sink or is used for food production, meaning that harvest for bioenergy will either deplete the existing carbon stock, or displace food production (Searchinger et al. 2015; Searchinger et al. 2017).

Searchinger et al. (2017) argue that bioenergy must be sourced from wastes and residues, rather than harvested from dedicated land-use, to be carbon neutral, due to the 'carbon opportunity cost'

per hectare of land (that bioenergy production decreases the carbon carrying capacity of land). Given high demands on land for food production and other uses Searchinger et al. (2017) suggest that climate policy should not support bioenergy from energy crops and other dedicated uses of land, such as wood harvest for bioenergy. The supply of waste and residues as a bioenergy source is always inherently limited (Miyake et al. 2012). The collection and use of wastes and agricultural residues present logistical and cost barriers, although the use of secondary residues (cascade utilization) may decrease logistical costs and trade-offs associated with waste use (Smith et al. 2014).

In conclusion, this brief overview of current debates around bioenergy use would suggest that the sustainable supply of bioenergy is limited to the lowest end of projected ranges; that sourcing bioenergy from forest harvest is not carbon neutral and any bioenergy from the 'dedicated use of land' is unlikely to be carbon neutral; and the use of residues and wastes for bioenergy is limited. A recent nature commentary from Field and Mach (2017, p.707) highlights the issues at stake, suggesting that converting land on the scale required for bioenergy in many modelled climate change mitigation scenarios would "pit climate change responses against food security and biodiversity protection".

Soil carbon sequestration

Significant land carbon sinks also occur outside the forest sector, meaning there is significant potential for restoration of degraded lands and enhanced sequestration potential outside of forested areas. Globally, there are an estimated 3.5 billion ha of degraded soils and desertified ecosystems (Lal et al. 2012), although estimates of the extent of degraded lands carries great uncertainties (Gibbs & Salmon 2015).

Soils contain the largest pool of terrestrial organic carbon and are a major source of atmospheric CO_2 (van Groenigen et al. 2014). Globally, mineral soils (i.e. excluding organic soils, such as peat) are estimated to contain approximately 1500 Gt C to a depth of one meter, which is double the amount of carbon in the atmosphere (Lam et al. 2013).

Soil carbon stocks (in mineral soils) are generally depleted as a result of agricultural activities, such as cropping – through, for instance, irrigation, use of fertilizers, different types of tillage, changes in crop density, and changes in crop varieties. Many studies have addressed the potential for land management to sequester soil carbon, and much attention has been given to the potentially large sink through changing agricultural practices to increase soil carbon stocks (Lal 2004; Lal et al. 2012; Stockmann et al. 2013). The last decade has seen a surge of interest and research into soil carbon as a cost competitive climate mitigation option (Lam et al. 2013; Minasny et al. 2017; Lugato et al. 2018; Hutchinson et al. 2007; Smith 2012).

Globally, the current flux from soil carbon is probably not far from zero, according to Lal et al. (2012) who have estimated the technical potential of carbon sequestration through restoration of degraded lands at 0.5–1.4 Gt C/year. High potential mitigation numbers such as these has given rise to a number of policy initiatives, such as the French governments '*quattre pour mille'*, which claims that just an 0.4 percent annual growth rate in soil carbon could offset 20-35% of annual GHG emissions globally (Minasny et al. 2017). However, others believe these figures are a "gross overestimate" due to the exclusion of increased methane and nitrous oxide emissions from the

figures and the extrapolation of research plot data to global extents (White et al. 2017, p.2; Lugato et al. 2018). Nevertheless soil carbon sequestration maintains prominence in many climate policies to meet short-term to medium-term targets.

Reviewing the literature on land management practices to increase soil carbon, and the limitations to this, reveals a general consensus that soil carbon sequestration is not a panacea for GHG emission reduction (Lugato et al. 2018; Mackey et al. 2013; Powlson et al. 2011; Smith, 2012; White et al. 2017). Leakage, additional emissions from fertilizers, and reversals are all key concerns. Powlson et al. (2011) warn that an over-emphasis on soil carbon sequestration may detract from other agricultural management practices that are at least as effective in combating climate change (such as slowing deforestation and increasing fertilizer efficiency) and conclude: "the limitations of C sequestration, whether in soil or vegetation, tend to be overlooked and misunderstood. As a consequence, we are concerned that the possibilities for climate change mitigation by this means may be exaggerated" (p. 43) "… even though these limitations have been clearly enunciated in numerous publications" (p. 52).

Degraded lands

On degraded agricultural lands, the potential contribution that tree cover can make to climate change mitigation has been significantly underestimated (Zomer et al. 2016). Agroforestry as a restoration technique has the potential to sequester and store significant amounts of biomass carbon in agricultural landscapes, without the permanence issues of soil carbon. Agroforestry involves planting trees as part of a system that will provide food or timber for subsistence or cash income, and generally involves a complex mixture of native and exotic trees and crop species which distinguishes them from monoculture crops (such as oil palm plantations). Agroforestry is already extensively practiced throughout tropical and developing countries, with an estimated 1.2 billion people around the world dependent upon mixed trees and farming systems (Venter et al. 2012).

A recent study by Zomer et al. (2016) gives the first globally comprehensive picture of the mitigation value of agroforestry. The authors estimate the above ground carbon stock of agricultural land globally at 45.3 Gt C, with 43% of all agricultural land having at least 10% tree cover in 2010, a 2% increase on the previous decade (Zomer et al. 2016). By including the biomass storage of trees in the agricultural landscape, Zomer et al. (2016) found a mean value of 21.4 tC ha/yr in 2010 - more than four times larger than the IPCC Tier 1 global estimate of 5 tC ha/yr. Between 2000 and 2010 Zomer et al. (2016) estimated an increase of 0.2 Gt C/yr of biomass carbon on agricultural land globally. By comparison, above-ground losses due to tropical land-use conversion are currently estimated at 0.6–1.2 Gt C/yr (Zomer et al. 2016).

However, there are strong regional differences in biomass storage (and tree cover) on agricultural lands, following climatic zones (with arid areas containing less tree-cover), but also social and land-use differences (Zomer et al. 2016). There are also strong correlations between population density, tree cover and subsistence farming, which particularly in the tropics frequently incorporates trees. These factors together mean that both tree cover and consequently biomass carbon on agricultural land tend to be higher in tropical regions, indicating that other regions have the potential for increasing biomass carbon on agricultural land, even within climatic limitations (Zomer et al. 2016). These findings show that existing tree cover on agricultural lands - thus far ignored in most global and regional calculations - and sequestering carbon via increases in the tree component on agricultural lands, are achievable routes to increasing CO_2 sequestration (Herder et al. 2017). Agroforestry systems are often associated with high conservation values compared to agriculture that does not incorporate trees and mixed-species plantings, and provide a wide variety of goods and ecosystem services (Zomer et al. 2016). Other co-benefits include increased habitat and landscape connectivity for biodiversity, decreased albedo, watershed conservation and in some cases positive impacts on hydrological cycles, as well as local livelihoods (Herder et al. 2017).

2.2.3 Land restoration potential

Radically different approaches to determining mitigation potential were taken across the studies assessed here. On the one hand, Houghton et al. (2015) estimate the potential of tropical forest sequestration based on halting all forest activities. The studies that looked at managed forests in the Northern Hemisphere (Lundmark et al. 2014; Smyth et al. 2014; Nabuurs et al. 2017; Böttcher 2018) assessed changed management practices over discrete areas of land, including improved utilization, increased harvest efficiency and increased growth, as well as an increase in harvested wood products (which bring climate mitigation benefits when substituted for more energy intensive products such as in buildings). It is worth noting that these changes in management practices resulted in relatively small gains in mitigation potential – less than 0.15 Gt C/yr removals compared to 4 Gt C/yr estimated by Houghton's approach of restoring and reforesting tropical forest areas. A more recent study from Houghton and Nassikas (2017) found significant mitigation potential in temperate and boreal forests through long-lived harvested wood products, the mitigation value of which has long been contested (Winjum et al. 1998).

Zomer et al. (2016), in contrast, found large potential for increased sequestration though increasing tree cover on agricultural lands, while soil carbon sequestration was considered to have limited potential for climate mitigation (White et al. 2017; Powlson et al. 2011; Lugato et al. 2018; Lam et al. 2013). Table 2.3 summarizes the mitigation potential from the studies discussed above.

	Change in management practices	*Land area*	*Current sink/source (-) (+)*	*Mitigation potential (removals)*	*source*
Tropical	Sequestration potential with no timber harvest or swidden agriculture in tropical forests & 500 Mha reforestation	Humid tropical forests	+1.3 Gt / yr	4 Gt C/yr	*Houghton et al. 2015*
	Sequestration potential with no timber harvest or swidden agriculture in tropical forests	Humid tropical forests	+1.3 Gt / yr	3.3 Gt C/yr	*Houghton &Nassikas 2017*
	Reforestation on previously forested land	472 Mha tropical forests		2.17 Gt C/yr	*Griscom et al. 2017*
Temperate	Climate smart forestry (better management, abandoned farmlands and bioenergy substitution)	159 Mha EU forests (managed and unmanaged)	- 0.13 Gt C /yr baseline emissions (managed forests)	0.12 Gt C/yr by 2030	*Nabuurs et al. 2017*
	Ecological forest management (restoration, reduced harvest and protected areas)	10.5 Mha German forests		0.015 Gt C/yr averaged over 2012-2102	*Bottcher et al 2017*
	Reforestation on previously forested land	206 Mha temperate forests		0.57 Gt C/yr	*Griscom et al. 2017*
Boreal	Better utilization, reduced harvest and long lived HWP	232 Mha Canadian managed forest	- 0.02 Gt C /yr in Canada (managed forests)	0.009 Mt CO_2/yr averaged 2015-2050 (cumulative 1180 Mt CO_2e in 2050)	*Smyth et al. 2015*
	Increased growth and HWPs	22 Mha managed forest in Sweden		0.15 GT C/yr (over 1990-2105 time-period).	*Lundmark et al. 2014*
Agricultural soils	No till agriculture	Global (3/4 ice-free land)	Net-zero	8 Gt C cumulative by 2050	*Canadell & Schulze 2014*
Degraded lands	Increase trees in agricultural landscapes	2216 million ha of degraded land	Net-zero	0.2 Gt C/yr increased biomass carbon on ag. land between 2000-2010	*Zomer et al. 2016*

Table 2.3: An overview of potential for carbon sequestration across different biomes, spatial scales and management activities

More research is needed to determine the theoretical potential of carbon sequestration through forest regrowth across all forest biomes, with differing land-use and management regimes along with the potential for reduced demand, to arrive at a viable strategy for the mitigation contribution of the world's forest areas. Bioenergy is not included in Table 2.3 because of uncertainties in sustainable supply and carbon-neutral bioenergy, technological scale-up (in the case of BECCS), and noted impacts due to the scale of land required. These issues associated with bioenergy are explored in further detail in Chapters 5 and 6, while the potential of other land-based mitigation options, including trade-offs and synergies with sustainable development objectives, are assessed in Chapter 6.

2. 2 Global demand for land

After examining the potential for enhanced forest carbon sinks globally to contribute to climate mitigation, this section will examine the context of increasing competition for land with an increasing global population and increased consumption, and the new demands placed on land through the recent focus on land-based climate mitigation. How these overlapping and competing demands on land interact, affecting both climate mitigation and sustainable development goals, is a core concern of this thesis.

Changes in land cover have caused the most pressing environmental issues in recent decades (Alexandratos & Bruinsma 2012). Land and water resources are now much more stressed than in the past and are becoming scarcer, both in quantitative terms (per capita) and qualitative terms, following soil degradation, salinization of irrigated areas and competition from uses other than for food production (Alexandratos & Bruinsma 2012). Globally, land is becoming a scarce resource (Lambin & Meyfroidt 2011) with predictions that by 2050 we will need twice as much productive land as now sits idle (Canadell & Schulze 2014). Land management will require a 'global commons' approach to manage land-based production and consumption footprints in a sustainable and equitable way (Creutzig 2017).

2.2.1 Land Availability

Currently, about three quarters of Earth's ice-free land area is used by humans for cropping, livestock grazing, and forestry (Canadell & Schulze 2014). Agriculture is a key driver of land-use change. During the 1980s and 1990s more than half of new agricultural land across the tropics came at the expense of intact forests, with an additional third from disturbed forests (Gibbs & Salmon 2015), raising concerns about environmental integrity and biodiversity globally (Lambin & Meyfroidt 2011). The rate of loss of natural forest was 6.5 Mha per year for the period 2010–2015, representing a slowdown from 10.6 Mha per year in the previous decades (FAO 2016). Hence to date, the most significant form of land conversion is expansion of crop and pastoral land into natural ecosystems, making agriculture, food security and protection of natural ecosystems inextricably interlinked, and increasingly difficult to balance in a context of global land scarcity (Lambin & Meyfroidt 2011).

Land category (Mha)	*1990*	*2014*	*2030*	*2050*	*2080*
Ice-free land	13,000				
Agriculture area	4831	4972			
Arable land	1408	1417		1661[α]	1630[α]
Permanent crops	1194	1546	1672	1772[β]	1937[β]
Pasture	3302	3315	3030	3385[β]	3335[β]
Forest (total)	4128	3999	3761[β]	3698[β]	3595[β]
Primary forests	1312	1279			
Naturally regenerating forests	2627	2432			
Planted forests	1879	2901	+172-324		
Other land	4110	4121	+120 for urbanization		

Table 2.4: Current and projected demand for land by land-use category

Source: figures for 1990 and 2014 from FAO 2016; figures for 2030 adapted from Lambin & Meyfroidt unless otherwise indicated: [α]Alexandratos & Bruinsma 2012; [β]IIASA SSP database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about).

2.2.2 Demand for Land

Land demand assessments find that more land is required by 2050 than exists free of ice or barren soil (Canadell & Schulze 2014, Creutzig 2017). When looked at separately, there may appear to be enough available land for certain objectives, such as global agriculture production (Alexandratos & Bruinsma 2012), but when taken together, the different demands on land from sectors including agriculture, timber and fibre, bioenergy and land for conservation and urban expansion create a picture of projected land scarcity. Creutzig (2017) shows that it is in particular land for climate mitigation, specifically for negative emissions from forests and bioenergy, which exceeds land availability. While a moderate increase in land for crops by 2050 is in line with FAO projections, additional land demands for expanded forest plantations and bioenergy crops will certainly exceed land availability, pitting mitigation against food production. In this section I explore the predicted

land demand from agricultural commodities, bioenergy and forest harvest, to understand the overlapping and competing demands on land.

Land demand associated with food and agricultural products

Globally, the conversion of land to croplands has been responsible for the greatest loss of carbon from land-use change (91 Gt C over the period 1850–2005) (Houghton, 2012). The area harvested for industrial wood is larger than the cumulative area of forest cleared for croplands, yet the emissions from croplands are larger because the changes in carbon stocks per hectare are large when lands, especially forests, are converted to croplands. The FAO predicts that global demand for agricultural products (crop and livestock products for both food and non-food uses) will grow by 60% by 2050 (compared to 2005/7 levels), largely due to growth in incomes and global population, two key drivers of demand (Alexandratos & Bruinsma 2012).

Estimates of future land availability for cropland expansion vary considerably. One study suggests 445 Mha of 'spare land' suitable for cropping is available (non-forested, non-protected and sparsely populated) - mostly in Latin American grasslands and African savannahs (Lambin & Meyfroidt 2011). Although it is not forested, converting this land to agriculture will still generate environmental and social costs, due to high biodiversity values and existing social uses such as use by agro-pastoralists. There are predictions that the current land reserve could be exhausted as early as in the late 2020s, and at the latest by 2050, with a total additional land demand in 2030 of 285-792 Mha (Lambin & Meyfroidt 2011). This suggests that global land scarcity is already an urgent priority.

The FAO, on the other hand, suggest that three times this amount (1.4 billion ha) of prime land is available that could be brought into cultivation if needed, although it acknowledges that this would be at the expense of pastures and would require considerable infrastructure investment to bring remote areas into production (Alexandratos & Bruinsma 2012). The FAO does not expect that this land will be needed, with net land under crops projected to increase by 70 Mha by 2050 (increase

in developing countries, decline in developed, and excluding bioenergy demand) (Alexandratos & Bruinsma 2012). This does not mean that land constraints do not exist, given the unsuitability of much of the 'spare' land for agricultural production (due to remoteness, need for infrastructure development, etc.). Both studies agree that the majority (90% according to the FAO) of spare land available for cultivation is in Latin America and sub-Saharan Africa, with almost none available for agricultural expansion in Southern Asia, Western Asia and Northern Africa, presenting significant geographical constraints (Alexandratos & Bruinsma 2012; Lambin & Meyfroidt 2011).

Other research suggests much greater future land demand for agriculture than does the FAO, with a total increase of 1000 Mha of agricultural land - an area twice as large as the land identified as abandoned, marginal or of low quality - expected to feed 9 billion people by 2050 (Canadell & Schulze 2014). Differences in future estimations of land demand for agriculture are often due to differing expectations for yield increase, with the FAO expecting most future food demand to be met through yield and efficiency increases rather than land expansion (Alexandratos & Bruinsma 2012). However, growth of crop yields has slowed down considerably, with yield increase often over-estimated in the literature (Alexandratos & Bruinsma 2012). Searchinger and Heimlich (2015) argue that any yield increase could be assumed to help meet growing demand for food

Due to the difficulty in quantifying demand-side measures, projections of future land demand generally do not take account of dietary change and reduction in food waste, both of which could significantly reduce land area required for food production without compromising food security. Introducing the concept of "Human Appropriation of Land for Food" (HALF), Alexander et al. (2016) isolate the effects of diets on agricultural land areas, including the potential consequences of shifts in consumer food preferences. The authors find that agricultural land-use area requirements could vary over a 14-fold range, but minimizing land required for food production depends on reducing consumption of animal products, and targeting waste and over-consumption (Alexander et al. 2016).

Land demand associated with bioenergy crops

The production of biofuels has been of growing importance and could prove to be a major disruptive force in demand for land, but there is no discussion of solid bioenergy (such as wood pellets from forest harvest or residues) in the latest FAO update (Alexandratos & Bruinsma 2012). This oversight may lead to an overly optimistic assessment of land availability, where the FAO concludes "at the global level there should be no major constraints to increasing agricultural produce by the amounts required to satisfy the additional demand generated by population and income growth to 2050" (Alexandratos & Bruinsma 2012, p.17). Several studies have suggested a link between bioenergy policies, demand for cropland, and adverse land-use changes, especially deforestation in the Global South (Miyake et al. 2012; Haberl et al. 2011). When considering indirect land-use change, growing bioenergy demand in wealthier countries and regions such as the US and the EU is already impacting on land resources outside these regions and could trigger large-scale conversion of native forest and grasslands to bioenergy crops worldwide (Miyake et al. 2012).

Future projections of bioenergy potential and associated land requirements are large. Modelled mitigation pathways compatible with the Paris Agreement's temperature targets require unprecedented rates of land-use change when viewed within an historical context, exceeding - by more than threefold - the observed expansion of the most rapidly expanding commodity crop (Turner et al. 2018). Turner et al. (2018) highlight the challenges implied in presuming the ready availability of large-scale biomass-based carbon-dioxide removal if reliant on extensive land conversion. Estimates put the required land-conversion for bioenergy crops at 500 Mha (Tavoni & Tol 2010; Tavoni & Socolow 2013), between 470 and 3,590 Mha (Canadell & Schulze, 2014), or up to as much as 8 billion ha of land according to the IEA (International Energy Agency 2016).

The FAO suggests that constraining biofuel expansion to land not suitable for food crop production is unlikely in a market-driven rather than regulatory global economic environment (Alexandratos & Bruinsma 2012). It warns "given the disproportionately large size of the energy markets relative

to those for food and the stronger economic position of those demanding more energy vs. those needing more food, care must be taken to protect access to food by vulnerable population groups in the face of rising food prices" (Alexandratos & Bruinsma 2012, p.18). Deploying bioenergy on any scale would require effective governance networks with global reach to manage trade-offs and work against perverse outcomes (Schellnhuber 2009; Creutzig 2017).

Land demand associated with forest expansion

While forest loss and the drivers to forest loss are generally of greater concern, the risk that forest expansion for mitigation purposes could threaten food security, biodiversity and other land uses is a growing threat.

The FAO shows the largest drivers of forest loss now and projected for 2050 are cropland expansion, and urban and infrastructure development; with pastureland, timber and fuelwood extraction and mining behind those (FAO 2016). This does not show the potential for intact forests to be converted to forest plantations, or for an expansion of forest plantations for mitigation purposes to increase competition for land in the future.

While some studies have suggested that as much as 3 billion ha of land could be covered in forest plantations to mitigate climate change (Humpenöder et al. 2014), most future projections for the expansion of planted forests for climate mitigation converge on a figure of 300 Mha (Creutzig 2017). This additional land pressure arises from the identified potentials to sequester 0.2–1.5 Gt C per year in new forests and plantations requiring land areas of up to 345 Mha, which would be equivalent to increasing the current forested area by 18% (Canadell & Schulze 2014). Restoration of degraded forests, in contrast to reforestation and afforestation, does not require additional land but is instead restoring the functional capacity of an existing land-use (Houghton et al. 2015; Böttcher 2018).

2.2.3 Uncertainty in land availability estimates

There is large uncertainty in land-cover estimates (current and future), which is one of the key reasons that emissions from land-use are the most uncertain in the global carbon budget (Alexander et al. 2016). Analysis from different climate models incorporating land-use shows a large range in land cover projections, with the highest variability occurring in future cropland areas, although global pasture and forest areas also show on-going uncertainty (Alexander et al. 2016). The authors conclude that a higher degree of uncertainty exists in land use projections than is currently included in climate or earth system projections, calling into question the proportional contribution of land use to global emissions, and our knowledge of the potential for changes in land management practices to contribute to mitigation (Alexander et al. 2016).

Degraded lands are perhaps the most uncertain in global land cover estimates, with estimates of total degraded area varying from less than 1 billion ha to over 6 billion ha, with equally wide disagreement in their spatial distribution (Gibbs & Salmon 2015). This raises the risk of overestimating the availability of potentially productive land, which may divert attention from efforts to reduce food and agricultural waste or the demand for land-intensive commodities. In terms of the social implications of this uncertainty, See et al. show that "lack of accurate maps on the extent of global cropland, and particularly the spatial distribution of major crop types, hampers policy and strategic investment and could potentially impede efforts to improve food security in an environment characterized by continued market volatility and a changing climate" (2015, p.37). They conclude that there is a pressing need for the provision of spatially explicit cropland datasets at a global scale (See et al. 2015).

It is often suggested that additional land for climate mitigation, whether through forest plantations or bioenergy crops, will use degraded or marginal lands. However, the sustainability of the use of these lands is controversial and uncertain for several reasons - available land may be smaller than estimated, may require high resource inputs resulting in environmental impacts, and land may have high conservation and/or biodiversity values (Miyake et al. 2012). Indeed, what are sometimes

regarded as marginal lands can be grasslands of high biodiversity value (Burrascano et al. 2016), which are considered to be important for biodiversity conservation and contain high soil carbon pools. Gibbs and Salmon conclude that "efforts to map degraded lands often aim to identify regions that could be converted to uses deemed more productive, particularly biofuel production. However, most studies ignore the social and environmental constraints and trade-offs associated with using such lands. Even a precise map of the physical area of degraded land would significantly overestimate its potential by neglecting its myriad social, environmental, and political constraints" (Gibbs & Salmon 2015, p.19).

The socio-economic and social outcomes of targeting degraded lands are also questionable. In India, Africa, and other developing regions, marginal land is an important part of the livelihood of smallholder farmers and the rural poor (Miyake et al. 2012). Without existing social uses of the land being taken into account, and without ground-based estimates of the geographic location and spatial extent and current uses of such land, political efforts for large-scale conversion of land-use will either not eventuate, or cause unacceptable social and environmental impacts. Land-use accounting, incentives and governance systems need to be spatially explicit to reflect geographic variations in land attributes and production systems (Lambin & Meyfroidt 2011).

2.3 The politics of land in the UN climate regime

This section traces the history of how land came to be included in the UNFCCC, through the Kyoto Protocol and now the Paris Agreement, and the potential implications and the role of land-based mitigation in a post-Paris, zero-carbon world. A body of literature has emerged that examines the development of policies to deal with terrestrial carbon in the UNFCCC from a critical social science perspective (Backstrand & Lövbrand 2006; Fogel 2005; Lövbrand 2004; Lövbrand 2009). More recently it has expanded to include avoided deforestation (Gupta et al. 2012), and land carbon sinks in Australian policy making (Pearse 2013). This body of literature subjects the technical practices of terrestrial carbon accounting to social science scrutiny, drawing on strands of political ecology,

science and technology studies and Foucauldian governmentality studies to gain insight into the interplay between 'expert knowledge', power and politics in the making of international climate policy.

The literature refers to the 'politics of expertise' which could be defined as a limited group of experts "who define, assess and (often implicitly) conceptualize the solutions to the problems they put forward" (Hajer 1995), while non-scientific discourses are excluded (Wesselink et al. 2013). Close links between knowledge making-authority and decision making-authority advantages those with greater access to knowledge resources (Fogel 2005; Backstrand & Lövbrand 2006). These analyses suggest that translation of such knowledge into institutional forms could result in an expert-led (technocratic) approach, which risks overlooking political struggles over environmental control and rights to resources, even though these may be the underlying cause of the issues the experts are attempting to address (Easterly 2014; Jones et al. 2014; Ferguson 1994). I use this literature to examine the power-knowledge relationships at play in negotiations over the inclusion of the land sector, first in the Kyoto Protocol, and then in the Paris Agreement.

The inclusion of land in the Kyoto Protocol

The UNFCCC was established at the Rio 'Earth Summit" (the UN Conference on Environment and Development) in 1992. The ultimate objective of the UNFCCC is "to prevent dangerous anthropocentric interference with the climate system" (United Nations 1992, Article 2). There is no direct reference to 'land' in the Convention, although agriculture and forestry are listed alongside other mitigation sectors (Article 4(c)). The key reference to land in the Convention is the commitment in Article 4(d) to "promote and cooperate in the conservation and enhancement… of sinks and reservoirs of all greenhouse gases… including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems".

A significant step towards the central goal of the UNFCCC was agreement of the Kyoto Protocol, an international treaty aimed at reducing developed country emissions. Negotiations on the Kyoto Protocol initially focused on industrial emissions. Developed countries with large forest areas that were a net sink introduced the idea of 'net-emissions' into Kyoto discussions (Lövbrand 2004). Proposals for the inclusion of the land-use sector (known as land-use, land-use change and forestry, or LULUCF) were contentious, with some Parties arguing that due to accounting complexities, accounting for terrestrial sinks could become a distraction from reducing emissions from fossil fuel use (Falkowski et al. 2000; Houghton 2003). Others felt that incentives were needed to reduce deforestation, which is a significant contributor to GHG emissions (Schlamadinger et al. 2007).

During negotiations for the Kyoto Protocol, several powerful Parties, including the US, Canada and Australia, would not agree to legally binding climate obligations until they secured agreement that terrestrial sinks could be included in emission reductions on the basis of a net accounting system (Lövbrand 2004; Fogel 2005). The German Advisory Council on Global Change (WGBU) noted that this approach "harbors some danger" (WGBU 1998, p.2) as the difficulties associated with verifying emissions from terrestrial carbon undermines the verifiability of overall reduction targets. Inclusion of terrestrial carbon into the climate regime inevitably raises technical questions,

granting international expert networks a central role in climate governance, and turning the science-policy interface into a key site for political intervention (Lövbrand 2009).

Analyses of negotiations on LULUCF reveal how scientific expertise emerged as a key site of political bargaining (Lövbrand 2009), demonstrating the mutual co-production of science and policy (Fogel 2005; Lövbrand 2009). Viewing the problem through a technical lens displaces the need to confront issues of values and ethics (Stevenson 2013), concerns which are paramount in any approach to land sector governance. Fogel documents the "widely differing and opposing views" on how unanswered questions about the Protocol's biotic carbon sequestration provisions should be resolved in the production of an IPCC Special Report on LULUCF produced in 2000, and the way in which states worked to influence and control the scientific content of the report to their political ends (2005, p.196). Political pressure by some states on scientific outcomes resulted in an under-representation of social and natural science risks, with 'technical' information - pertaining to the quantitative impact of various measures better presented, influencing subsequent policy debates and contributing to the legitimization of biotic carbon sequestration in the Protocol (Fogel 2005).

Reducing emissions from deforestation in developing countries

Currently all Parties to the UNFCCC report on their land sector emissions, while developed country Parties are additionally required to account for some land-use emissions and removals under the Kyoto Protocol. Reporting and accounting differ in that reporting can be understood as accumulating data and providing information, while accounting involves comparing reported quantities against a target.

The contentious issues outlined above around including sinks in the Kyoto Protocol led to a situation where LULUCF accounting rules in the Protocol are complex and fragmented, with only a small group of experts able to engage in the development of these rules (Canaveira 2014; Macintosh 2011). These accounting rules, and their normative implications, are analyzed in some

detail in Chapter 4. While LULUCF applies only to developed countries with mitigation obligations under the Kyoto Protocol, the emerging framework on reducing emissions from deforestation and forest degradation (REDD+) in developing countries, despite efforts to maintain simplicity and transparency, has according to some also resulted in non-transparent and complex accounting rules (Gupta et al. 2012; Parker et al. 2014). REDD+ accounting systems are being developed by a handful of international experts, with little or no transparency around the implication of these systems for the vast majority of forest stakeholders (Parker et al. 2014).

Decisions at the UNFCCC on REDD+ have been analyzed as exercising disciplinary power through systems to monitor, report and verify changes in carbon emissions from reduced deforestation (through standardization, simplification and erasing the local), while also mobilizing counter-expertise (Gupta et al. 2012). Gupta et al., (2012) argue that knowledge practices are not neutral, but are always active interventions that perform and alter the real world phenomena they seek to represent, and that the process of commensuration of terrestrial carbon creates accounting practices that constitute certain ways of seeing the forest while constraining others. Lövbrand (2009) calls this the production and validation of knowledge claims, which are then translated into political authority. Gupta et al., (2012) put forward the idea of carbon accountability – to denote both how forest carbon is accounted for, and the need to hold to account those doing so. The authors argue that asking whose knowledge to take into account paves the way for a normative take on carbon accountability - raising questions of who is empowered or disempowered by global climate governance arrangements (Gupta et al. 2012).

Land under the Paris Agreement

The negotiation of a new post-2020 agreement 'applicable to all' was seen by some as an opening to review the inclusion of land-use in the same accounting framework as industrial emissions, as happened in the Kyoto Protocol (Mackey et al. 2013). Sterk and Hermwille (2013) review a broad range of possible approaches to mitigation commitments from the literature against criteria of effectiveness and equity, concluding that all options have advantages and disadvantages, and countries should be "strongly encouraged to think about the future climate regime more multi-dimensionally than only in terms of GHGs" (Sterk & Hermwille 2013, p.282).

In the lead-up to the 2015 Paris Agreement, UNFCCC negotiations were focused on two tracks: negotiating an international post 2020 climate agreement, and increasing ambition for the pre-2020 period. These negotiations took place 'under the Convention', meaning the principle of common but differentiated responsibilities (CBDR) applies to the resulting Paris Agreement, widely interpreted as an expectation for differentiation in the nature and scale of commitments for different Parties, although how such differentiation will be determined among Parties remains unresolved (Winkler & Rajamani 2013; Rajamani & Werksman 2018).

The concern of this thesis, however, is the implication of a global agreement 'applicable to all' for governance outcomes in the land sector. Land sector mitigation is currently approached very differently in developed and developing countries. As summarized above, all parties currently report to the Convention on emissions from all sectors, including the land sector. However only developed countries that are signatories to the Kyoto Protocol are required to account for their land sector emissions, via LULUCF. Developing country parties can also opt-in to voluntary accounting for emissions from forest loss under REDD+, a scheme in its infancy. The Paris Agreement did little to resolve these two distinct approaches to reporting and accounting for forests, with both LULUCF and REDD+ included in a separate article of the Agreement (Article 5), in some senses maintaining the separate approach for developed and developed countries.

A second key implication arising from the Paris Agreement for the land sector is that the long-term mitigation objective of the Agreement is to 'balance sources and sinks' – the achievement of which places land sector governance at the heart of global climate governance. The myriad debates and controversies that have sprung from this new role for land in the global climate regime are analyzed further throughout this thesis, particularly in Chapter 4, which looks at how the land sector came to occupy a central role in the Paris Agreement, and Chapter 5, which looks at the governance implications of the inclusion of land-based removals in climate models.

2.4 Key themes and research gaps

The core aim of this thesis is to ask in what ways does the use of climate science construct and enable land-based mitigation to meet the 'balance' objective of the Paris Agreement, and is this compatible with the Agreements 'sustainable development' objective? This is an issue of critical concern because the Paris Agreement's goal for very low emissions scenarios according to modelled pathways requires removal of carbon-dioxide from the atmosphere, putting the spotlight on terrestrial carbon sinks. In this chapter, I have reviewed the literature on the terrestrial carbon cycle, an understanding of which is a crucial foundation for thinking about land-based mitigation. I then reviewed the key land-based mitigation options – through forests, bioenergy, soils, and degraded lands. Finally, I reviewed the literature that looks at how power and politics play a role in the uptake of 'sequestration science' into global climate governance in the context of LULUCF and REDD+ in the climate regime.

This review has revealed several research gaps. The first pertains to the way critical social science literature has approached the critique of the politics of expertise in the case of land based mitigation. The second concerns the uptake, or legitimization, of large-scale bioenergy in modelled climate policies when science over the carbon neutrality, land availability, and sustainable potential for bioenergy remain so uncertain. The third concerns the type of mitigation options that are

considered (and not considered) in the literature on enhanced sequestration potential in the land sector. These research gaps are addressed in turn below.

Theme 1 – The co-production of terrestrial carbon science with policy demands

While this topic has been well covered in the case of LULUCF accounting rules, there has been less recent literature on this topic, such as in relation to REDD+, and very little literature examining the question of science and politics around land-use in the Paris climate agreement. The concerns of an expert-led, or technocratic approach to land-sector governance which played out in the development of LULUCF and REDD+ can be seen from this review to be current concerns in the context of land-use for climate mitigation. Global climate models assume availability of land for bioenergy production to remove emissions from the atmosphere as a 'least-cost' option to achieving the Paris Agreements temperature limits, even while the literature warns of the potential for bioenergy to actually increase atmospheric emissions when forests are harvested and land is converted, and in the context of a lack of spatially explicit knowledge over the location, extent, and current uses of land already assumed to be available for future mitigation needs (see Section 2.1.2 on bioenergy, and Section 2.2.2). The research gap identified here relates to how terrestrial carbon science is co-produced with policy demands to arrive at the technocratic approach to land sector governance reflected under the Paris Agreement, which places land in a central role in the Agreement's mitigation goal. This gap is the focus of the first research question, on the co-production of science and policy in the context of land-based mitigation under the Paris Agreement.

Theme 2 – Scale of assumed reliance on land for carbon removal

Section 2.1.2 identifies a mismatch between the scale of bioenergy assumed in modelled scenarios for future climate mitigation and potential for sustainable supply in the literature, as well as potential barriers to other projected mitigation options (such as afforestation or soil carbon sequestration). Projected reliance on scaled-up bioenergy as a mitigation option in modelled scenarios reliant on BECCS is large: Field and Mach note the "truly massive use of a technology with little real-world experience and poorly known economics" (2017, p.707).

As outlined in section 2.1.2, there is currently little evidence that bioenergy could be scaled up to levels expected in global climate models, with an increasing number of studies casting doubt on the ability to generate beyond 100 EJ/yr from bioenergy without massive social and environmental consequences (Heck et al. 2018; Boysen et al. 2017). Combined with uncertainties over the location and extent of degraded lands reviewed in section 2.2.2, demand for dedicated land for bioenergy or other forms of land based mitigation may exacerbate risks of biodiversity loss, food insecurity and displacement of rural communities.

Determining how the current assumptions for land-based mitigation have been included in modelled pathways compatible with the Paris Agreement is a pressing research priority. I will address this issues in the context of research question number 2 – how have negative emissions been legitimized as key mitigation options under the Paris Agreement? In line with research question 3, I will also examine the implications of this scale of land-based mitigation for biodiversity and food protection.

Theme 3 – lack of attention to ecosystem-based mitigation

There are several insights to be drawn from the detailed studies into changed forest management practices reviewed above. Most of the literature addressing this topic focuses on a narrow spectrum of land management practices, namely sustainable land intensification; avoided emissions (from deforestation and agriculture); and bioenergy, involving mitigation via fuel substitution, or by contributing to sequestration using CCS - see for example, the comprehensive review in Canadell & Schulze (2014), which concludes that these are the three most promising mitigation options for the land sector. Whether for bioenergy or carbon storage via harvested wood products, if increased demand for forest products shortens harvest rotation lengths the losses in biomass will be greater than the accumulations in wood products or the uptake of subsequent forest regrowth, yielding a net overall loss of carbon from land (as has been the case globally over the last 150 years or more) (Houghton, 2012).

What tends to be largely overlooked is the role that intact forests play in climate stabilization, and the potential for restoration and regrowth of degraded ecosystems to contribute to climate mitigation. Even a recent publication that overviewed 'natural climate solutions' to meet the 2 °C temperature goal focused on interventions in managed forests and agricultural landscapes, rather than ecosystem-based approaches (Griscom et al. 2017). Restoration of degraded lands, through ecosystem restoration or ecosystem-based agricultural practices such as increasing trees in agricultural landscapes, offers significant mitigation potential, but previous and existing land-uses must be considered. Some degraded lands were once forests or savannas and may be better suited to restoration to those ecosystems, and their associated carbon sinks, rather than undergoing further development for agriculture. Leakage may also occur as communities evicted from such degraded areas are pushed into the forest frontier, or they could face reduced livelihoods if pushed onto even lower quality lands (Gibbs & Salmon 2015).

A research gap in the literature on enhancing the land carbon sink is a focus on restoration of natural ecosystems, with the attendant co-benefits of livelihoods and biodiversity that ecosystem-based approaches would entail. Research question 3 – the implications of a technocratic governance approach to land-based mitigation strategies – aims to address this gap by developing governance approaches to land-based mitigation based on broader social objectives aligned with the sustainable development goals.

Chapter 3

Conceptual framework and research design

This thesis seeks to illuminate policy-making processes regarding land use in the climate regime by exploring the links between knowledge production and policy making at the science-policy interface, in order to answer the core research question: in what ways does the use of climate science construct and enable land-based mitigation to meet the 'balance' objective of the Paris Agreement, and is this compatible with the Agreements 'sustainable development' objective? This thesis takes a cross-disciplinary approach - I draw heavily on the natural sciences to start with a robust understanding of the terrestrial carbon cycle, as presented in the previous chapter, in order to examine land-sector governance in international climate policy. The previous chapter also included a critical analysis of the inclusion of land in the climate regime, describing a technocratic, or 'expert-led' approach to land sector governance in international climate politics (see Section 2.3). The rest of the thesis advances this work by looking first at how these same political dynamics played out in the lead-up to and during negotiations on the Paris Agreement, and second at the post-Paris implications for global climate governance of the current approach to land-use under the Paris Agreement and in international climate policy.

To examine how an expert-led approach came to dominate global climate governance, it is necessary to look at the relationship between knowledge, power and policy. Based on a social constructivist understanding that science is a powerful political tool (Miller & Edwards 2001a), I take a critical social theory perspective to examine the implications of a technocratic governance approach for the role of land in climate mitigation policies. Taking as a starting point the Paris Agreement's objective to balance sources and sinks in the context of sustainable development, I argue that the sustainable development objective of the Paris Agreement requires an emancipatory

standpoint to "help point towards ways of strengthening environmental governance by enabling policymakers to better identify, assess and take into account the normative dimensions of expertise" (Miller & Edwards 2001b). Based on the above discussion, I construct a principled framework for critique of the Paris Agreement, with a stronger emphasis on meeting the sustainable development aspects of its core objectives.

This chapter is structured as follows: Section 3.1 develops a conceptual framework, situating this research within critical science studies and outlining which analytical tools are used to draw out the normative implications of the thesis' research questions. Section 3.2 outlines the methodological approach taken, drawing on conceptual approaches that are compatible across methods used. Whilst guided by critical and normative theories, this research is empirically grounded – the primary intention is to apply theory to current policy problems rather than to advance a particular theoretical approach. This can be termed "theory-driven practice", where the aim is "deconstructing underlying theoretical and methodological problematizations, whilst moving beyond critique to suggest alternative forms of action" (Griggs et al. 2007, p.1).

3.1 Conceptual framework

Critical social science approaches have in common a skepticism towards the reductive assumptions that knowledge is transferred linearly to policy, or the belief that decisions cascade from international to local levels, to examine the function of power, and how this creates and legitimizes certain types of knowledge at the risk of excluding or silencing others. Critical theory in particular carries a specific agenda around emancipation and justice. It seeks to unmask power, illuminating the winners and losers of entrenched social structures (Morrow & Brown 1994).

Analyses that focus on the power-knowledge nexus and the generation of knowledge are heavily indebted to the French philosopher Michel Foucault. However, in this thesis I avoid those post-structuralist theories derived from Foucault's work that resist any claim to an objective truth,

instead situating my work within a more normative political theory that focuses on the outcomes of power-knowledge process, and the governance implications of this for the most vulnerable. This can be seen as a social justice lens, which focuses attention on protecting the most vulnerable from the impacts of climate change, as well as from potentially negative impacts of climate policies, and further aligning climate responses to enhance objectives related to social justice goals (such as sustainable development) (Patterson et al. 2018). In this sense, social justice guides what can be judged as ethically 'good' (and therefore socially legitimate) goals to pursue in contrast to goals that create winners and losers (advantaging some actors at the expense of others). These questions are inherently normative and value-based, and hence outside the realm of science, yet the production of scientific knowledge has an empowering and disempowering function, raising questions of legitimacy. The degree to which knowledge production takes account of, and hence contributes to, the agreed normative goals and socially sanctioned objectives in the Paris Agreement is the central concern of this thesis.

I draw on critical perspectives in science and technology studies (STS), which see legitimacy as linked to accountability, to examine the role of power in knowledge creation and the interactions of science and policy. STS encompasses many theoretical and methodological perspectives, directed at investigating the place of science and technology in society. STS draws on the sociology of science work done in the 1970s (Latour & Woolgar 1979) but avoids both social and scientific determinism by treating nature and society symmetrically (Jasanoff 2004d). More recent work, which is public policy oriented (theory-driven research) and focused on democracy and expertise includes writings by Jasanoff and Wynne (Jasanoff & Wynne 1998), Miller and Edwards (2001a), and Hulme (2010) among others.

Social studies of science regularly focus on the role of international science and policy elites, with the idea that we "need to attend carefully to the institutional, cultural and political forces that shape the production and validation of scientific arguments as well as their uptake" (Miller & Edwards 2001b, p.11). STS has been widely applied to questions of environmental sustainability, given the

central role of science in environmental policy-making. The 1980s saw a shift to eco-modernization, with environmental policy making largely approached as a technical problem (Hajer, 1995). Jasanoff described this shift as a "utopian search for neutral approaches to conflict resolution, framed by objective, quantitative decision making techniques, such as vulnerability assessment, risk assessment, and cost benefit analysis", enabling a "technicalization" of environmental policy making (Jasanoff 1990, p.34). This focus on quantification aptly describes the approach to land-sector governance in the UNFCCC, where an objective (and therefore purportedly neutral) approach or assessment of the problem is paramount to political credibility.

Insights from STS can help to interrogate the process by which knowledge is created - revealing the centrality of social and political values to the presentation of what appears as 'rational/scientific' (Keeley & Scoones 2000). Realist approaches typically assume that knowledge production takes place outside of social domains and are therefore independent from sources of power (Jasanoff 2004c). But if, instead, the construction of knowledge is a "deeply political process" then we must investigate how and why ideas acquire consensual status (Miller 2001). Scientific questions (about nature) often have significant normative dimensions (Jasanoff 1990; Wynne 2009) and these dimensions can be seen to be central to problems discussed in this thesis – such as the standardization of accounting for forest carbon emissions, or the ubiquitous use of negative emissions in modelled mitigation pathways.

How land-use is standardized and dealt with in international policy settings is a natural question for STS and critical social science studies, which examine the process of mutual construction of science, knowledge and policy. For instance, Gupta et al. (2012) consider the concept of the 'carbonization' of forest governance – when forests are rendered legible through their carbon content only. They describe how computer models and satellite imagery represent "an immensely powerful technology of simplification that makes it possible to detach forest space from its local context and turn it into an orderable undifferentiated mass of carbon to be managed" (Boyd 2010, and Lovell 2011, in Gupta et al. 2012, p.727). These examples of categorizing and ordering the

world in ways that shape social practices raise questions over the interests that are represented, and the neutrality of such representation. In the realm of international policy-making, science derives trust and credibility from objectivity, yet science is value laden in the sense that it privileges certain voices, ways of knowing, and interpretation of nature over others, foreclosing debate over political options (Miller 2001). This empowering and disempowering function of science raises questions of legitimacy, where "the very act of using science to inform public choices confers power on some actors in the policy process while removing it from others" (Miller 2001, p.265).

In the rest of this chapter I take a closer look at the concept of power, the methodological approaches to uncover power in the context of knowledge production at the science-policy interface, and propose evaluative criteria for the legitimate use of science in public policy making. Noting Barnett and Duvall's observation that "power works in various forms and has various expressions that cannot be captured by a single formulation" (2005, p.41), I first outline their 'taxonomy of power' to understand the multiple conceptions of power. Next I take a deeper look at the concept of co-production to understand the use of science and knowledge production in policy making. Co-production can be used as a lens to illuminate questions around how politics gets built into science, and the implications of this in a technical policy setting that is heavily reliant on scientific expertise, such as the role of the land sector in low emissions pathways.

3.1.1 Power

The concept of power is central to global governance. Understanding of directly exercised power - the control of one actor over another - has heavily influenced international relations, and informs much of realist thought (Barnett & Duvall 2005). The realist conception of power presumes that powerful states follow the rules when the rules promote their interests, and that weaker states follow the rules in order to avoid punishment (Barnett & Duvall 2005). Although it has become commonplace for constructivists to stress the centrality of the concept of power, the indirect effects of power are not always included in analyses. Barnett and Duvall note that while "constructivists

have emphasized how underlying normative structures constitute actors' identities and interests, they have rarely treated these normative structures themselves as defined and infused by power" (2005, p.41). Guzzini, for example, stresses that power requires agency, but considers indirect (as opposed to direct) effects to be 'governance' rather than power (Guzzini 2005). Barnett and Duvall emphasize that no single concept can capture the forms of power in international politics, and urge scholars to see how "the multiple concepts capture the different and interrelated ways in which actors are enabled and constrained in determining their circumstances" (2005, p.67). To this end, they provide a useful 'taxonomy of power' to assist scholars in developing "a conceptual framework that encourages rigorous attention to power in its different forms" (Barnett & Duvall 2005, p.42).

Barnett and Duvall define power as the "production, in and through social relations, of effects that shape the capacities of actors to determine their fate" (2005, p.42). Their taxonomy is based on two dimensions of how power is exercised – the specificity of social relations through which power is exercised, and the kinds of social relations through which power works, producing four types of power – compulsory, structural, institutional and productive (Figure 3.1). The first analytical dimension, the specificity of power - refers to the direct (compulsory and structural), or diffuse (institutional and productive), social relations through which power works. Direct power refers to an observable, traceable interaction between subject and object. Yet power also works through indirect and socially diffuse relations, often through the (formal or informal) rules of institutions (institutional power), or the social processes and systems of knowledge and discursive practices through which meaning is produced and co-produced (productive power) (Hajer 1995; Barnett & Duvall 2005). Observing power only when there is a direct or causal connection makes it difficult to analyze the spatially and temporally distant relations though which power works when "evolving rules and decision-making procedures can shape outcomes in ways that favour some groups over others" (Barnett & Duvall 2005, p.48).

The second aspect of Barnett and Duvall's taxonomy concerns the social relations of power – interactional or constitutive. Here we see whether power works through the interactions of specific actors (which can also be indirect interactions, such as through the rules of institutions); or whether power works through social relations of constitution - through the ways social situations of actors are constituted (social structures), or the production of knowledge and meaning. This interactional / constitutional division overlays the direct and diffuse relations of power to produce a taxonomy (Figure 3.1).

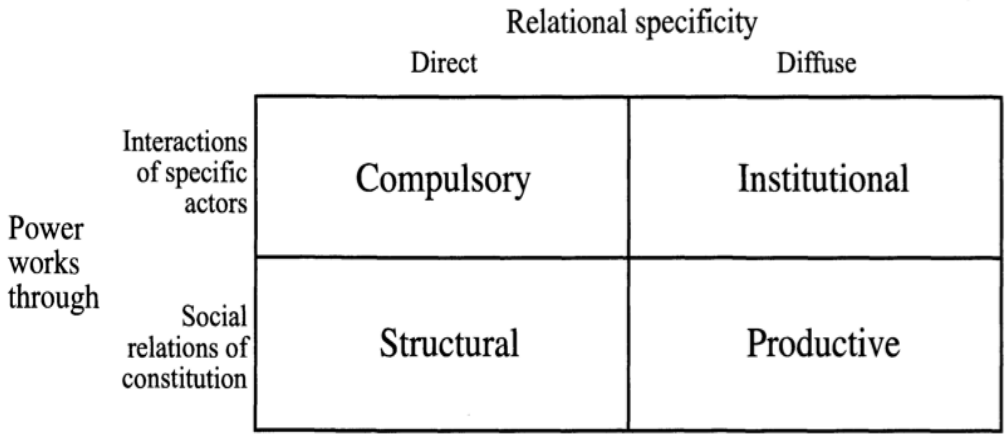

Figure 3.1. Taxonomy of power
Source: Barnett and Duvall 2005

Structural power and productive power overlap in many ways, as both concern how the social capacities of actors are socially produced. Barnett and Duvall explain "both are attentive to constitutive social processes that are, themselves, not controlled by specific actors, but that are effected only through the meaningful practices of actors" (2005, p.55). The difference is that productive power works through diffuse social processes (systems of knowledge and discursive practices) rather than the differential privileges of structure identified in structural power (such as class or social role). Barnett and Duvall assert that attention to productive power is therefore post-structural, concerning discourses, social processes and the systems of knowledge "through which

meaning is produced, fixed, lived, experienced, and transformed" (2005, p.55). Yet at the same time these social processes and systems of knowledge are also shaped by, and situated in, social structures, such as education, culture and systems of knowledge.

These social structures can also be viewed as (informal) institutions, and there are close overlaps between institutional power and structural power. Those focused on institutions may see structure and institution as interchangeable (in the rules, procedures and norms of formal and informal institutions). Barnett and Duvall maintain a distinction between structural power, where actors are defined by the identities of the (often mutually determinative) social structures they inhabit (and reproduce rather than resist these social structures, such as through class), and institutional power, where the way institutions are shaped and formed indirectly exerts control over others, whether formal (through rulemaking) or informal (through discourse and cultural artefacts). For the purposes of my work, the distinction between structural power (directly constitutive), and institutional power (indirectly interactional), is less important than the commonalities – the disproportionate power of certain social roles within social structures, or certain institutions, on the construction of knowledge, and the value-based assumptions that get promoted.

In the context of global climate governance, this disproportionate power can be seen to rest with climate science, itself inherently reliant on climate modelling, where the rules, discourses and cultures of institutions around climate science and climate modelling set the context of what does and does not count as valid knowledge for climate governance. Investigating how and why global climate policy comes to be based on certain kinds of knowledge and not others and the distributional impacts of this, is a core concern of this thesis. Edwards (2001) shows how the IPCC, as a scientific institution, used strategies of co-production to shore up its fledgling authority, with experts and expert knowledge, considered to be politically neutral agents, accorded significant power to define problems of global policy. Hence power does not necessarily rest with individual actors, but is lodged in the structure of the institution, making trust and credibility an important component of institutional, and knowledge-making, legitimacy.

Barnett and Duvall's taxonomy highlights the multiple and interconnected ways in which power operates in practices of global governance. They note that direct expressions of power concern who governs in global governance, whereas indirect expressions (institutional and productive) concern "not who governs, but instead how the governing capacities of actors are produced, how those capacities shape governance processes and outcomes, and how bodies of knowledge create subjects that are to be, at least in part, self-regulating and disciplined" (2005, p.62). This taxonomy allow us to work from realist to critical approaches when examining the effects of power, yet their taxonomy falls short as it fails to account for the power in rational persuasion, and in doing so assumes that all power is adversarial. Barnett and Duvall's taxonomy views the effects of power as necessarily enabling those with power and entailing constraints or impositions on the agency of those disempowered. This approach does not consider distinctions between power as domination or power as socially sanctioned and legitimate.

Why is a discussion of power important? Because the processes through which knowledge is produced form what can be judged as having normatively 'good' and 'bad' effects in the context of global climate governance. Normatively we can judge these effects in accordance with collectively agreed goals and principles, such as those in the Paris Agreement, which have political legitimacy on the basis of the multilateral procedures by which they were negotiated. My interest here is to better understand whether knowledge production for climate policy aligns outcomes with normative goals sanctioned by the international community – namely that climate mitigation is achieved without undermining sustainable development. The question I am asking, then, is not about the robustness of the scientific process but the legitimacy of the knowledge produced, where I define that legitimacy through alignment with socially sanctioned goals. While power, in all its forms, shapes the production of knowledge, it is not always adversarial. Rather than a domination of one type of knowledge over another, certain processes of knowledge construction could be viewed as a legitimate expression of power if the processes of knowledge production include or take account of socially sanctioned objectives. Barnett and Duvall's taxonomy does not allow us

to explore the mutual constitution of knowledge and social relations in its cooperative, rather than adversarial function. To do this I turn to the concept of co-production - the mutual constitution of science and society.

3.1.2 Co-production in science and technology studies

STS has been applied to many areas of scholarship, including environmental globalism (Jasanoff & Martello 2004), climate modelling (Miller & Edwards 2001a), and the role of science advisors in public policy making (Jasanoff 1990; Pielke 2007). Building on this work from the 1990s and early 2000s, STS scholars elaborated a new analytical approach - co-production - which helps to clarify "how power originates, where it gets lodged, who wields it, by what means, with what effect" (Jasanoff 2004d, p.5). As a further step to studies of the history of science, which looked at the role of culture in shaping science (Kuhn 1962), coproduction can be seen as part of the post-Kuhnian, post-normal scientific paradigm, taking social interaction as the primary concern (Jasanoff 2004a, p.276). Science here is seen as political – both power and culture feature in the mutual shaping of nature and society (Latour 2017).

Therefore, the interaction of science and policy can be seen as a process of mutual construction where, through the interaction of knowledge and power, science and society are co-produced (Jasanoff 2004c). In other words, science is not dissociated from policy objectives and social values, rather science and policy emerge in tandem. Jasanoff has written extensively about co-production, describing it as an 'idiom' – an analytical tool rather than a fully-fledged theory - intended to illuminate rather than to prove or disprove a theory. "The co-productionist idiom stresses… the constant interplay of the cognitive, the material, the social and the normative" (Jasanoff 2004b, p.38). Co-production provides a valuable analytical lens for examining questions of power and knowledge in global governance, as it looks at how knowledge making is incorporated into governance, and how practices of governance influence the making and use of knowledge (Jasanoff 2004d).

Jasanoff (2004b) describes work in the co-productionist idiom as falling into two strands - constitutive (what there is and how the 'is' is constituted) and interactional (how we find out about it, through systems of knowledge). Constitutive accounts of co-production are more concerned with metaphysics and ontology, while interactional accounts are more concerned with epistemology – "less with what is and more with what we know about it" (Jasanoff 2004b, p.19). However, both involve the construction and deployment of knowledge (the emergence of new knowledge, or resolving knowledge conflicts within existing structures and institutions) and hence both require the invoking and resolving of boundaries to gain legitimacy. This process of mutual construction of science and policy is often obscured from view - the co-production lens uncovers this and leads us back to "the practices and processes - often battles - that lead to the closure of scientific controversies, the black-boxing of uncertainties and the establishment of knowledge" (Keeley & Scoones 2003, p.36). The concept of boundary work - how boundary conflicts between science and policy arise and are resolved (Gieryn 1999) - is important here in challenging the assumption of science as an autonomous sphere whose norms are constituted independently of other forms of social activity.

Co-production is often applied to issues of environmental governance, where themes of institutional and epistemic emergence are of relevance because of the frequent invoking of scientific knowledge to settle political controversies in this arena (Sarewitz 2004). The ongoing controversy over the role of land-use in climate mitigation provides an example of a knowledge controversy, or an epistemic debate - the process by which the products of technoscience are made intelligible and portable across boundaries (Jasanoff 2004a). Jasanoff suggests that the possibility of critical engagement is most apparent in emerging orders: "It is at the point of emergence, before things are completely stabilized or black-boxed, that one most easily observes the mutual uptake of the social and the natural" (2004a, p.278). Given that "important normative choices get made at the phase of emergence" (Jasanoff 2004a, p.278), it is in the current epistemic battle around the reliance of future climate mitigation pathways on land-based carbon removal that I look to understand the

assumptions underlying these decisions, and the value judgments and alignments on which these assumptions are based.

While co-production, as an analytical lens, offers an effective means to investigate the question of value judgements embedded in technical discussions, it is also important to remain attentive to the multiple conceptions of power at play in the political and institutional settings under study (climate science and the UNFCCC). Jasanoff observes that co-production accounts generally add to existing theories of power "refining our understanding of what power means, and how it is formed and exercised" (Jasanoff 2004a, p.279). Neither Barnett and Duvall's taxonomy of power nor a co-production lens provide enough guidance to judge deficiencies in the processes of science knowledge production from an emancipatory standpoint. But looking at the multiple conceptions of power with a critical theory lens provides a normative yardstick from which to judge the legitimacy of the co-production of scientific input into policy.

3.1.3 Co-production and power: a synthesis

Power has emerged as a central question in critical constructivist approaches. Jasanoff suggests that co-production offers political scientists new ways of thinking about power, "highlighting the often invisible role of knowledges, expertise, technical practices and material objects in shaping …relations of authority" (2004d, p.4), further suggesting that "perhaps the most important question raised by interactional STS work on science and the state concerns the direction of the influence of knowledge on power" (2004b, p.36). Here I map co-productionist approaches onto Barnett and Duvall's power taxonomy, to use in guiding an emancipatory analysis of the role of power in the context of knowledge production for climate policy. The co-production idiom provides a way to see power as both "lodged in social structures which constrain the production of potentially dissident knowledge" and simultaneously as "fluid and continually renegotiable" (Jasanoff 2004b, p.36).

Parallels with Barnett and Duvall's taxonomy of power - where the multiple concepts of power "capture the different and interrelated ways in which actors are enabled and constrained in determining their circumstances" - can be seen here (2005, p.67). Barnett and Duvall (2005, p.60) refer to the concept of productive power as applied to global governance, which "highlights how the discourses and institutions of international relations contingently produce particular kinds of actors with associated social powers, self-understandings, and performative practices". Here we see a parallel between productive power, and co-production, where both refer to the mutually constitutive shaping of natural and social orders, which is itself infused with power.

That knowledge is a form of power is not a new idea - STS work on co-production relies heavily on Foucault (Jasanoff 2004c). Yet co-production accentuates this proposition by reminding us that "not only does knowledge constitute power, but equally, power frames and organizes knowledge" (Jasanoff 2004a, p.280). Coproduction alerts us to the fact that power is constituted as much through marginalized alternatives as through the "positive adoption of dominant viewpoints" (Jasanoff 2004a, p.280). This opens up a role for thinking about power operating between equals, or in a cooperative fashion, rather than the adversarial relations of power described by Barnett and Duvall (2005). Their analytical taxonomy sees power as static - whether interactive or constitutive, direct, or indirect and diffuse – the expressions and effects of power are seen as deeply embedded. Co-production, on the other hand, describes a particular relational dynamic of 'co-productive power' since the effects of the scientific and political discourses co-produce each sphere of activity along with the boundary between them. The co-productive lens then, renders visible the process of knowledge production in the mutual constitution of science and society, thereby subjecting these processes to critical judgement and evaluation. Taking co-production as a central frame, we see the mutual shaping of science and society, even as multiple conceptions of power are varyingly at play. Rather than seeing power statically through a four cell matrix, co-production is a symmetrical analysis of dynamics, with the possibility for power to be lodged equally, or distributed across,

different spheres, as "co-production blurs the boundaries of natural and the social, and sees them acting on each other, where most social sciences keep them separate" (Jasanoff 2004a, p.278).

While Barnett and Duvall (2005) emphasize that multiple conceptions of power are simultaneously present in international politics, examining power from a constructivist perspective is necessary in order to understand the role of power in knowledge production, where politics gets built into knowledge (Jasanoff 2004d, p.9). On the other hand, while co-production offers an appropriate analytical lens for my work exploring the role of power and politics in land governance, Barnett and Duvall's taxonomy of power adds to this by clarifying how different types of power produce effects, and where to look for these. However, the synthesis presented here goes beyond identifying types of power to understanding the normative aspects of power, in the sense that certain types of practices can be more empowering or less empowering for certain actors, and that power is not always constraining but can also be enabling. I integrate different types of power under an over-arching critical social theory that is emancipatory – it draws on politically accepted social goals within the international climate regime (the goals of sustainable development), but interprets these in a critical emancipatory sense. This entails a reflexive normative standpoint on the part of the researcher that views a just, and therefore legitimate, outcome as one that seeks to avoid domination over actors who are marginalized in the context of global climate governance, who are at the same time those most vulnerable to climate impacts. This emancipatory approach in the context of scientific knowledge production has parallels to Jasanoff's concept of 'serviceable truth': "a state of knowledge that satisfies tests of scientific acceptability and supports reasoned decision-making, but also assures those exposed to risk that their interests have not been sacrificed on the altar of an impossible scientific certainty" (Jasanoff 1990, p.250).

3.2 Research design

The core question of this thesis is to ask in what ways does the use of climate science construct and enable land-based mitigation to meet the 'balance' objective of the Paris Agreement, and is this compatible with the Agreements 'sustainable development' objective?

I do this by:

- Analyzing the co-production of climate policy demands and 'sequestration science';
- Identifying the legitimization and uptake of scientific knowledge in the international climate regime (through formal and informal rules and regulations, social structures and underlying discourses); and
- Evaluating the potential governance outcomes of these processes with respect to sustainable development.

All of these research tasks seek to uncover the role of power. Bailey and Revell call for the repoliticizing of climate governance research, through engagement with "the political immediacies shaping attempts to govern climate change" (2015, p.527). They argue that without this, "key strands of political science research on climate governance risks becoming apolitical" (Bailey & Revell 2015, p.527). Observing where power is exercised and how can be seen as a way to identify the politics shaping climate governance. A co-production framework also enables normative analysis by "following power into places where current social theory seldom thinks to look for it", such as in climate models (Jasanoff 2004b, p.42).

In developing a methodology to analyze the co-production of science and technology in society, Jasanoff suggests that it is important to think about what levels of social aggregation and in what kinds of institutional spaces it makes sense to look for co-production (Jasanoff 2004d). Jasanoff identifies four focal areas that give rise to co-production: the emergence and stabilization of new objects or phenomena; the framing and resolution of controversy; the standardization of knowledge or technology; and the cultural practices of science and technology in contexts that endow them with meaning (Jasanoff 2004d).

Among these focal areas, the epistemological basis of this research is concerned with the framing and resolution of controversy, in terms of the epistemic battles over sequestration science that have and still are occurring – through the development of land-use accounting rules (which also involves standardization – 'making things the same'), and through the inclusion of 'negative emissions' into modelled climate mitigation pathways. Jasanoff (2004d, p.6) also suggests that co-production occurs along well-documented pathways, and identifies four such pathways that can be used to explore co-production:

- Making identities
- Making institutions
- Making discourses
- Making representations

These provide a bridge between STS and more traditional political and social analysis, which also revolve around similar analytical categories, although making discourses and making representations significantly overlap, and are also the processes that produce identities. Therefore all of these pathways need to be explored in analyzing co-production. In this section I use the synthesis of power and of co-production from the preceding section to develop a critical framework of knowledge production, in order to judge outputs as legitimate or illegitimate processes of co-production based on the extent to which normative framings have been considered in the knowledge production process.

3.2.1 Methodological approach: Policy process analysis

This research concerns the construction of scientific knowledge and its inclusion in the policy process, that is, the production and legitimization of scientific knowledge. In analyzing the co-production of science for climate policy and the multiple conceptions of power at play in processes of policy-making, I will relate these to the concept of a policy process framework put forward by Keeley and Scoones (2000). Keeley and Scoones explore three contrasting explanations of policy

change - that policy reflects political interests; that change reflects the actions of actor-networks; that policy is a product of discourse (Keeley & Scoones 2003).

However, their framework is focused on the role of actors in the policy process, involving direct and indirect forms of power (compulsory, structural and productive (the latter via discourses)). This research will focus more on the indirect forms of power, through institutional power and productive power, where co-production takes place through the representations of knowledge (involving identities and discourses) that are enacted to maintain power and authority in the battle for ideas in the policy space. An adaptation to Keeley and Scoones' framework, to focus on institutional and productive power, was used to guide the development of the methodological approach used here. This framework starts with an examination of the policy questions being asked; looks at the role of (formal and informal) institutions, and asks which discursive ideas and forms of representation dominate in the policy making space, mapping these to Jasanoff's co-production pathways (Figure 3.3).

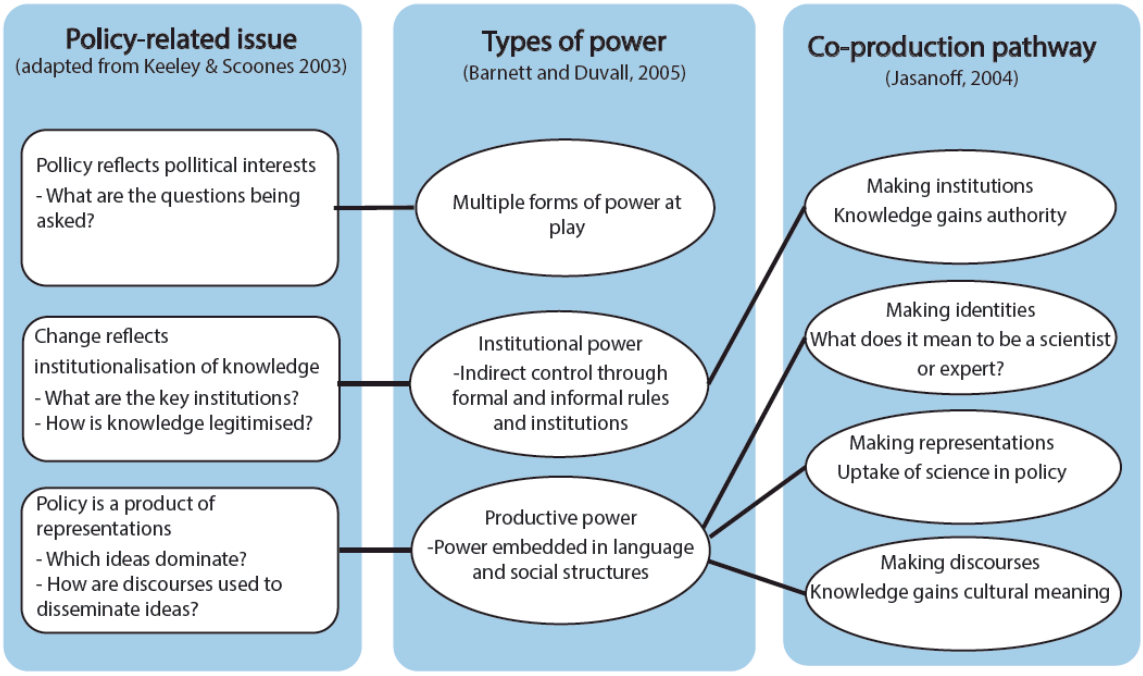

Figure 3.2 Policy process framework, power and co-production

An epistemic community, the concept introduced to international relations by Peter Haas (Haas 1992), can be defined as a type of knowledge elite which shares similar basic assumptions, transcends national boundaries, and influences policy-making. While Keeley and Scoones (2003) understood epistemic communities as a type of actor-oriented approach – emphasizing the practices of individuals and groups of actors connected in network, Hass identifies an epistemic community as a network of recognized experts with authoritative claim to policy relevant knowledge within a specific domain (Haas 1992). Hence it is the way these communities represent and enact authority that is of interest here, rather than the actions of individuals in the community. Knowledge controversies, or 'epistemic battles' provide sites for studying the expressions of power inherent in the creation of knowledge, norms and institutions. Focusing on productive power enables an identification of epistemic communities influencing knowledge production related to land-based mitigation in international climate policy, and interactions at the science-policy interface. An analysis of the co-production of knowledge that is also attendant to the multiple conceptions of power described by Barnett and Duvall (2003) enables an examination of the power exercised in socially contested efforts to set and fix meanings as expressions of productive power.

Many of the critical science studies reviewed in Section 2.3 do not evaluate the technical aspects of the knowledge generation process being studied (c.f. Gupta et al. 2012) yet often it is the controversies in the development of technical methodologies and ideas that reveal what is at stake, and which ultimately determine winners and losers. Hence it is important to also analyze the content, as well as the politics, of the technical debates that are used to shape policy. At the same time, to analyze environmental discourses merely as technical decision making on a physical problem misses the essentially social questions that are implicated in these debates (Hajer 1995, p.18). This research takes a cross-disciplinary approach, starting with an in-depth understanding of the carbon cycle and sequestration science being debated, and then applying a methodology focused on the role of power in processes of scientific knowledge production.

All of the typical co-production pathways outlined by Jasanoff are important (and overlapping) when looking to illuminate the production and uptake of scientific knowledge. Institutions can be understood as vehicles through which the validity of new knowledge can be accredited. In the context of this research, the IPCC is a key institution that legitimizes knowledge production for climate policy including policy-related processes such as terrestrial carbon accounting and future mitigation technologies, while the UNFCCC is key in providing a political space to assimilate knowledge. I propose that legitimacy in the production and uptake of knowledge for policy is achieved when the questions and purpose informing knowledge production (and the policy process) are broadly defined based on socially sanctioned goals and objectives. For my purposes here, I will define these socially sanctioned goals as the SDGs, given these are an existing set of globally agreed normative objectives, and in line with the goal of the Paris to pursue mitigation 'in the context of' sustainable development. When questions are narrowly framed and exclude key social concerns, framed by the SDGs in this case, I will consider this as illegitimate co-production in the context of science-policy input to achieving the goals of the Paris Agreement that are based on both mitigation objectives (balancing sources and sinks) and social objectives (equity and sustainable development goals). In this way, I can identify normatively 'good' and 'bad' examples of co-production, using criteria defined by the SDGs to guide methodological work in identifying the legitimacy of co-production and the normative outcomes of this.

Theorizing conceptions of power in relation to the legitimacy of the policy and knowledge production process allows me to understand which aspects of the policy making process are influenced and shaped by which conceptions of power, and how these relate to the pathways of co-production. This enables me to identify the methodological tools most relevant to illuminate the co-production of science and policy, including the role of power. Figure 3.4 illustrates the links between the research questions, the conceptual framework involving power and the methodological approach taken to assess legitimate and illegitimate co-production, as described above.

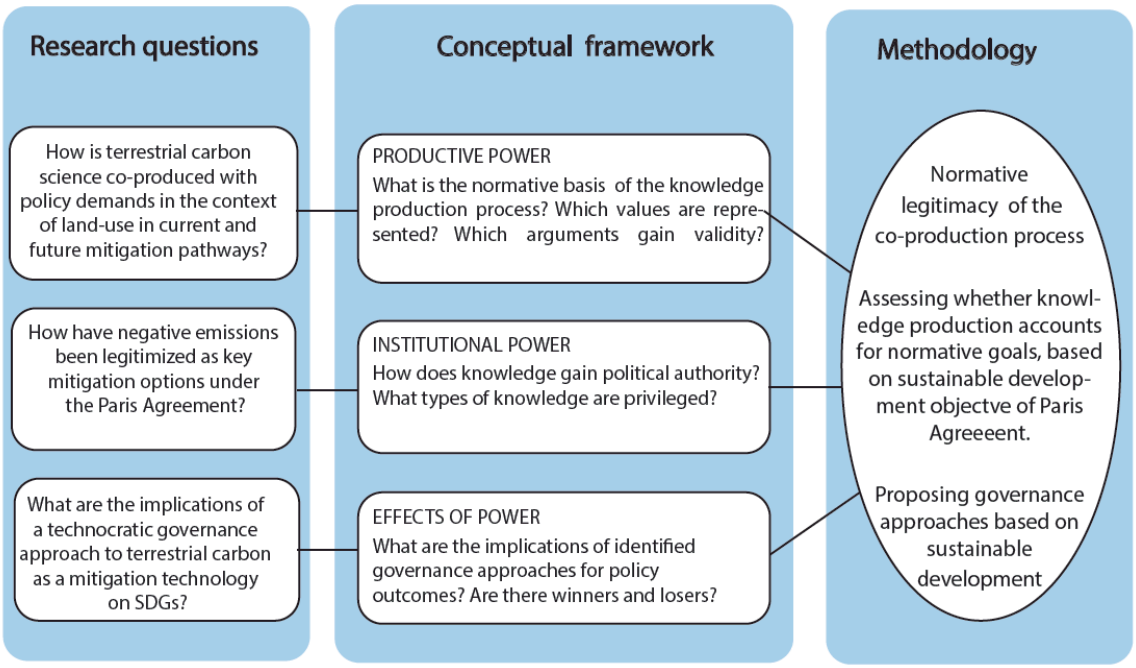

Figure 3.3: Research questions, conceptual framework and methodological approach

3.2.2 Research methods

The UNFCCC is an example of what Keeley and Scoones refer to as a "site for the mutual construction of science and policy on an international stage, where knowledge and practices are exchanged, discourses are shaped and political actions are designed" (2003, p.28). The negotiation of a the Paris Agreement under the UNFCCC opened up the 'discursive space,' by creating potential for new representations of knowledge and ideas to emerge, in a way that has not happened since negotiation of the Kyoto Protocol. Hence I have chosen the UNFCCC as a study site that will yield rich insights into power-knowledge dynamics within an institutional framework. As Hajer (1995, p.2) argues, "developments in environmental politics critically depend on the specific social construction of environmental problems." The institutional context in which policy debates occur co-determines what can be considered as credible. Hence it is not only what is being said which must be analyzed, but the institutional context in which this occurs, and the identities, interests and goals of the actors involved. Below I explain the methods I chose to examine the political use of land-use accounting rules in the UNFCCC, the legitimization and uptake into the

international climate policy discourse of modelled future climate mitigation pathways, and potential land-based mitigation pathways consistent with sustainable development objectives.

Three data sources were employed - interviews, participant observation at UNFCCC negotiations, and content analysis based on a range of different documents for the different research questions. These data sources were considered most appropriate when thinking about the core question, which asks how does the use of climate science construct and enable land-based mitigation to meet the 'balance' objective of the Paris Agreement, and is this compatible with the Agreements 'sustainable development' objective? To answer this question, and the subsidiary research questions presented in Figure 3.4, two sources of data were considered essential: the outcomes of the knowledge production processes I was assessing, and the inputs of both the scientists and policy experts involved in this process (as knowledge producers and knowledge users). Hence, selecting the most appropriate documents to analyze the outcomes of the knowledge production processes under investigation, as well as securing interviews with key scientists and policy makers in these processes was an important research stage. Data gathering for this thesis involved 'purposive sampling' (as opposed to random sampling) methods in order to target the data sources to the knowledge processes under study. Purposive sampling can also be justified in qualitative research because "the major concern is not to generalize the findings of the study to a broad population… but to maximize discovery of the patterns and problems that occur in the particular context under study" (Erlandson et al. 1993, p.82).

Analysis of the data produced by each of these approaches is described separately for each approach below. Overall, I take a mixed methods approach to data analysis. In line with critical social science studies, the methods are primarily qualitative, as qualitative approaches are most appropriate to answer the research questions here about how and why certain governance approaches to terrestrial carbon are taken, and the implications of these. I also include a quantitative analysis of modeled scenarios for climate mitigation, and draw on an extensive literature review of the terrestrial carbon cycle and sequestration science, in a cross-disciplinary manner.

The use of overlapping and multiple sources of data provide a basis for triangulation – where different sources of data can give greater confidence as to whether the aims of the research have been met and research questions answered. Also important is to be aware of how a mixed-methods approach may need to take into account multiple epistemologies or ways of knowing. Miller et al. argue that "ignoring the role of multiple ways of knowing, process, etc., in interdisciplinary research can torpedo efforts from the beginning" (Miller et al. 2008, in O'Neill et al. 2013, p.463). Methods must be justified in their ability to address both the environmental problem that initially motivated the research as well as the implications and challenges of the range of methodological choices that need to be made during the course of research. Participant observation at UNFCCC negotiating sessions was not considered a primary data source, but was particularly useful for triangulation and for being able to continually understand and adjust to challenges presented during the course of the research through contextualization within the site of study. The methods summarized below are organized according to the data collection method – these methods are also described more succinctly within the published paper that is included in each of the research chapters.

Interviews

Interviews were critical to answering research questions 1 and 2. For this purpose I conducted semi-structured interviews - interviews guided by a set of basic questions and issues to be explored, but without exact wording or sequence (Erlandson et al. 1993). (Interview questions used in Chapters 4 and 5 can be found in Appendix A). Interviews were used to develop the thesis' narrative about relevant policy developments; to identify co-production processes and legitimization strategies and to gain perspectives on the science-policy interface through talking to both scientists and practitioners.

The process of identifying who to interview formed part of the process of identifying key actors in the policy processes under investigation. Key actors were identified separately for the different

issues under consideration in Chapters 4 and 5 – on land-use accounting rules, and the inclusion of land-based mitigation in climate models. For Chapter 4, I identified a wide range of stakeholders - negotiators, scientists and observers - following international negotiations from developed and developing countries. I used a snowballing method to identify key stakeholders closely following the LULUCF process, and to a lesser extent REDD+, identifying new interviewees until stakeholder groups were adequately covered. This resulted in 21 interviews, mostly conducted in person during 2015 at UNFCCC negotiating sessions. This was considered sufficient to obtain views from the different stakeholder groups that were sought – with 14 land-use negotiators interviewed (seven from developed and seven from developing countries), three members of civil society and four academics. A higher number of interviews would have allowed for greater possibility to see a correlation or divergence in views, but given my own familiarity with the topic under investigation, interviewees were chosen from across the range of views typically present in UNFCCC policy space on land-use accounting.

For Chapter 5, interviewees were chosen by identifying IAM modellers involved in modelling the land-use components of the five IAMs under investigation, and policy makers who had engaged in developing national long-term climate strategies by the end of 2016. Out of this relatively small group of modellers and policy experts, 10 respondents were interviewed. In this case, I considered 10 interviews to be adequate because of the small community of integrated assessment modellers, and equally small community of policy-makers or advisors deeply familiar with the outputs of IAMs.

For soliciting interviewees engaged in the UNFCCC process, the identification of key actors was assisted by my knowledge of the process and actors under investigation, as well as scrutiny of current policy documents. The selection of IAM modellers was aided by the limited number of models under investigation, and hence the limited pool of potential interviewees who could be approached. Where possible, face-to-face interviews were conducted. Attendance at UNFCCC sessions during 2017, the time data-collection for Chapter 5 was being undertaken, facilitated

access to both policy experts engaged in the UNFCCC process, and integrated assessment modellers, who often attend these meetings.

Interviews were recorded, transcribed and analyzed for relevant content using NVivo. Interviews conducted for Chapter 4 were coded to eight thematic nodes: accounting rules; definitions; fungibility; integrity; principles; experts; science-policy; transparency. Interviews conducted for Chapter 5 were coded to four themes: uncertainty; feasibility; constraints; and responsibility. Coding allowed for content analysis to be developed, without losing the richness of the qualitative data. Due to the relatively small amount of nodes coded, data could be used in original form rather than assigned numbers. O'Neill et al. note that "balancing data richness versus generalizability is perhaps one of the most significant trade-offs that researchers confront when navigating their methodological choices" (2013, p.457).

Document analysis

Document analysis was an important data source for all research questions, although the form of 'document analysis' varied widely. For research question 1, content analysis of policy process documents was particularly important. This consisted of 43 party submissions made to the UNFCCC between January 2014 and June 2015 to Workstream 1 of the Ad-Hoc Working Group on the Durban Platform (ADP). Analysis of these submissions from a range of governments was used to triangulate data gained through interviews. For research question 2, document analysis was twofold: consisting of quantification of land-use variables from the latest generation of IAM scenarios for a 2 °C mitigation pathway; as well as an extensive literature review to determine sustainable limits to these variables proposed in the literature. Research question 3 depended on analyzing the objectives of relevant SDGs.

Institutional power can be seen in formal and informal rules and regulations, which relates to the UNFCCC institutional context, including the science-advisory role played by the IPCC. Productive power concerns systems of knowledge and meaning in the production of knowledge. Examining

discursive practices in document analysis (and interviews and participant observation) enabled an identification of how productive power works to privilege some voices and exclude others in policy making. For research question 1, country and observer submissions to the UNFCCC (as well as successive versions of decision-related documents) formed the primary documents for analysis. All submissions from countries during 2014 relevant to negotiations leading to the Paris Agreement were analyzed, and selected country submissions from 2015 were also analyzed when they included new information related to the research topic. To narrow the range of analysis, submissions were initially screened for new content as more recent submissions tend to build on older ones, and submissions can repeat each other. Analysis of submissions to the UNFCCC during 2014 and 2015, used in Chapter 4, are included as Appendix B. In addition, grey literature produced by interest groups, civil society, and indigenous peoples' organizations were important to ascertain the positioning of various stakeholders on the issues under study. The Paris Agreement was also an important document for analysis, as can be seen in the discussion in Chapter 4.

For research question 2, on the legitimization of negative emissions as key mitigation options, IAM models were quantitatively analyzed, based on variables available in the database for the Shared Socio-economic Pathways hosted by IIASA. These variables, related to level of bioenergy use and extent of land-use change, were then compared to a literature review for sustainable potential of these variables through to 2050 and 2100. Quantifying and presenting the land-use outputs was considered important to show what kinds of knowledge are privileged in a given institutional context, and subjecting this knowledge to scrutiny based on defined normative goals. These methods are described in detail in Chapter 5. The data retrieved from the IIASA database and all calculations used in Chapter 5 are included as Appendix C.

Research question 3, on the implications of technocratic governance approaches to terrestrial carbon mitigation, required an extensive analysis of the different objectives under the SDGs determined to be most reliant on land for their attainment: SDG 2: zero hunger; SDG 13: climate action; and SDG 15: life on land. These were compared to estimates from the literature on the

potential synergies and trade-offs of the various land-based negative emissions options on the attainment of these goals. The SDGs represent a consensus set of global objectives related to development, and it is important that increased demands for land from climate mitigation are assessed in the context of sustainable development objectives. Based on this evaluation, I propose an estimated potential for those negative emissions options that pose less risk of conflicts with sustainable development objectives, which can be considered as a governance approach based on an explicitly normative framework

Participant observation

While observation in qualitative research is defined as the "systematic description of events, behaviours and artifacts" (Marshall and Rossman 1989, in Erlandson et al. 1993), in the context of international negotiations, observation can also be a form of data collection parallel to document analysis, where observation of exchanges between countries add further detail and richness to the positions that are outlined in written submissions. In this sense, observation was primarily used as a form of triangulation, improving reliability of the research findings.

Participant observation was considered a secondary source of data collection to support the content analysis drawn from interviews and documents, but was nonetheless crucial, particularly for determining alliances between countries (often articulated during negotiations, but not presented in written submissions). Direct observation of negotiations also gives an insight into priority issues for different countries, and most importantly, makes clear who are the more influential countries or country groupings, as well as how other actors exert influence in the negotiation setting. Participant observation also allows for more nuanced analysis of country positions, and the uptake of scientific knowledge into these, through statements and interventions where negotiators often refer to technical versus political aspects of negotiations and the use of 'best available science'.

Participant observation, which informed the analysis for all three research questions, occurred during attendance at 12 UNFCCC intersessional sessions and conferences of the parties (COPs)

during the course of conducting research for this thesis, starting with COP 19 in Warsaw in December 2013, and finishing with COP 23 in Bonn in November 2017. Observation of negotiations was facilitated by my long engagement in the negotiation process (as an active observer since COP 15 in Copenhagen in 2009), enabling an in-depth understanding of exchanges between countries, references to past decisions, and the sometimes obscure structure of negotiation processes.

The use of participant observation raises ethical issues regarding my own role. As a member of several civil society networks, research input drew on resources that I accessed through my role as a participant in the process I set out to research. McNeil and St Clair (2011) term this approach, 'observant participation,' and identify three challenges that are particular to being an 'observer participant' which are relevant to address in my research. The first is an ethical question related to other actors in the process not being aware their actions are being observed for research, and not having given explicit consent. A similar ethical question arises with the use of 'off-the-record' statements and information that is not in the public domain.

Given that observers are allowed access to UNFCCC negotiations through politically agreed rules of procedure for the UNFCCC, and many of these observers are known to be from research institutions, it is reasonable to assume that government representatives know their participation is routinely being examined for research purposes, and all information I had access to could reasonably be assumed to be 'in the public domain'. In addition, all interviewees were guaranteed anonymity, to protect identification of participant views in a politically sensitive environment, where research publications were being produced even as negotiations on the topic under consideration continued.

The second two challenges raised by McNeil and St Clair (2011) are methodological concerns relating to the trustworthiness of conducting research based on participation in the field of study. One is whether my analysis could be biased by views I hold as an actor in the process. Another is

the extent to which I might influence the process I am studying. I have dealt with these concerns throughout the research process by building in reflexive assessment, while also acknowledging the impact of my own views on the research. First, in the introduction and in the conceptual framework for the research, I have declared my own position on the field of study as being one of concern that the sustainable development objectives of the Paris Agreement are achieved, as an integral part of the mitigation goal. In this sense, the research is explicitly normative. Second, the multiple research methods used builds in a form of triangulation, where I am drawing on the views of interview respondents, as well as content reflected in country submissions and statements, as well as quantitative analysis of model outputs, to gain multiple perspectives on the issues being studied.

Chapter 4

Evolution of land-based mitigation in the climate regime

Chapter 2 presented a background on the science of the terrestrial carbon cycle, the sequestration potential of various land-based mitigation options, global demands for land, and the politics of land in the international climate regime. Chapter 3 then developed a conceptual framework of the role of multiple types of power in shaping the co-production of policy with scientific knowledge. In this way, the previous chapters have provided a broad and comprehensive overview of the science and politics relevant when thinking about land-based mitigation in the context of global climate governance.

In this chapter, I take a closer look at the inclusion of land in the climate regime, and the contested politics of this. My interest is to show not only how knowledge and politics are intertwined, but also to draw attention to the governance outcomes that flow from this.

The politicization of science, whereby scientific knowledge is redeployed for political gain, is a much discussed challenge in the literature on the science–policy interface, and goes hand-in-hand with the scientization of politics - the increasing use of scientific evidence to justify political ends by removing scope for value-based political debate (Weingart 1999). The politicization of science refers to the manipulation of science for political gain, such as selective evoking of technical knowledge to further a specific political agenda (Gupta 2012). The scientization of politics may lead to the misuse of science: scientific research can be used to hide value judgements behind political positions and to obscure contentious issues in difficult debates (Weingart 1999). In this chapter I view these twin process as *governing expertise* and *governing by expertise*, in order to evaluate the governance outcomes that flow from particular types of co-production.

As discussed in Chapter 2, the climatic impact of terrestrial ecosystems remains highly uncertain, in terms of our understanding of their contribution to climate processes, our ability to accurately

monitor and measure terrestrial ecosystems and land-use change, and the potential for biological sinks to weaken as global warming increases. The political interest in carbon sequestration as a climate mitigation measure has put great pressure on scientists to produce results that reduce uncertainty, in order to include them in a global carbon accounting regime. While this has led to significant advances in forest and other landscape monitoring and greatly increased our understanding of global land-use change, it has at the same time lead to a highly technical approach to land use accounting rules (whether through sink provisions in the Kyoto Protocol, or, more recently, negotiating baselines for REDD+). Lövbrand characterized this as a shift to "politically mandated science" (2004, p.450). My tracing in this chapter of what has been called 'the sinks debate' shows how states, through enrolling scientific experts as representatives, have used science to legitimize and downplay risk and uncertainty, favoring policy approaches with less scientific credibility for political ends. I trace this debate in order to understand the way in which the (perceived) need for scientific precision in accounting for terrestrial emissions privileges expert knowledge in decision making, and the potential impacts on policy outcomes, and then apply these insights to the inclusion of land in the Paris Agreement.

Structurally, this chapter consists of a paper published in the journal *International Environmental Agreements* in 2016. The paper is included in full as Section 4.1, and contains a description of the purpose, background, research methods, discussion and conclusion relevant to the aims of this chapter.

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ORIGINAL PAPER

4.1 Governing by expertise: the contested politics of (accounting for) land-based mitigation in a new climate agreement

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Abstract This article analyzes the contested politics of including (and accounting for) land-based mitigation in a post-2020 climate agreement. Emissions from land have been only partially included to date within the United Nations Framework Convention on Climate Change and its Kyoto Protocol. The Paris Agreement, adopted in December 2015 and "applicable to all" for the post-2020 period, raises the possibility of unprecedented reliance on land-based mitigation. This has significant consequences for furthering both ambition and equity in global climate mitigation efforts. Yet, what are these consequences, and how have they manifested themselves in the existing (pre-2020) multilateral climate regime? What role do accounting rules for land-based mitigation play herein? In addressing these questions, we identify key dimensions of what we term the "governance by expertise" approach taken to land-based mitigation to date, which has served to reduce the environmental integrity of existing (developed country) mitigation efforts. Specifically, we analyze land-use accounting rules as a site of politics and highlight the "technicalization of politics" underway in this realm, which obscures the political implications of how land has been included to date. We conclude by considering whether the Paris Agreement institutionalizes similar dynamics, and the environmental integrity and equity implications of doing so.

Keywords Accounting · Climate governance · Equity · Land-based mitigation · Land-use, land-use change and forestry (LULUCF) · Negative emissions · Paris Agreement · United Nations Framework Convention on Climate Change (UNFCCC)

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1 Introduction

This article analyzes the contested politics of including (and accounting for) land-based mitigation in a post-2020 climate agreement. Emissions from agriculture and land-use contribute roughly a quarter of global greenhouse gas (GHG) emissions (IPCC 2014). Yet, these have been only partially included to date in the multilateral climate regime, which is centered around the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol. Under the auspices of these agreements, countries have sought for the last two decades to agree on guiding principles and binding obligations (for developed countries) to reduce their GHG emissions.

With the newly concluded Paris Agreement under the UNFCCC, adopted in December 2015 and "applicable to all" for the post-2020 era, the partial inclusion to date of the land sector looks set to change. Key elements of the Paris Agreement raise the possibility of unprecedented reliance on land-based mitigation. This includes the temperature goal to stay "well below" a temperature increase of 2 °C and to "pursue efforts" to limit temperature increase to 1.5 °C over pre-industrial levels (UNFCCC 2015, Article 2.1). Related to this is the long-term mitigation goal calling for a peaking of greenhouse gas emissions "as soon as possible" to be achieved through a "balance between anthropogenic emissions by sources and removals by sinks" (UNFCCC 2015, Article 4.1). The reference to "removals by sinks" implicates, inter alia, terrestrial sequestration of carbon emissions, i.e., the land sector.[1]

Much is at stake, given that the land sector is crucial to the pursuit of sustainable development and poverty eradication, and the most vulnerable populations depend upon land for food, fuel, and livelihoods. Added to this is the technical and political complexity inherent in monitoring land-based emissions. A key dilemma is thus how to secure land-based mitigation so as to enhance collective climate action, without undermining food security or other essential land-uses.

In this paper, we assess how the challenges of relying on land-based mitigation have been dealt with in existing (pre-2020) climate governance efforts. Our aim in doing so is to identify the consequences of pursuing similar approaches in the future. In particular, we focus on the *accounting rules* for the land sector developed within the UNFCCC's Kyoto Protocol, upon which a post-2020 climate regime is likely to build. We choose to focus on accounting rules because these rules have shaped the nature and scope of reliance on land-based mitigation in meeting current developed country emission reduction targets under the Kyoto Protocol. It is thus crucial and timely to understand the nature of these accounting rules, how they came to be negotiated, and their implications for ambitious and equitable pathways to future climate mitigation efforts by all.

In our paper, we view land sector accounting rules as a *site of political negotiations*, even as they are technically complex, obscure, and often inscrutable to those lacking requisite expertise. In analyzing the complex interplay between the technical and political in this realm, we advance the notion of "governing by expertise" in this article, which we argue has been the dominant approach to including land-based mitigation in the multilateral climate regime to date. Such an approach has entailed a *technicalization* of what are highly contested normative and political questions about who should do what, and how much, in combating climate change, and what role the land sector should play herein.

[1] Land is the only sector where CO_2 is not only emitted (via forest burning and clearing and land-use change for agriculture, among other activities), but also sequestered (via photosynthesis).

One caveat is important to note at the outset: A key conflict around land-based mitigation in the UNFCCC has centered on the scope and meaning of the term "land." While land generally refers to forests, agriculture, and other land-uses, developing countries have long opposed the inclusion of agriculture within multilateral climate mitigation efforts under the UNFCCC, given the potential adverse impacts on food security. Our analysis pertains thus to *carbon-related* terrestrial emissions, i.e., CO_2 emissions and removals from forests, soil carbon, and cropping and grazing activities, in line with current Intergovernmental Panel on Climate Change (IPCC) reporting guidelines on so-called LULUCF (land-use, land-use change and forestry) activities. This excludes consideration of non-CO_2 agricultural activities (such as livestock management and fertilizer use), which are the dominant sources of emissions from the agricultural sector.

We proceed as follows: We first distill lessons from the manner in which land-use, as understood above, has been included to date in the existing climate regime. Our discussion reveals a lack of environmental integrity in the current (accounting) approach to land sector inclusion.[2] We then review the architecture of target setting in the Paris Agreement and the envisaged role (and debates around accounting) for the land sector therein. We conclude with considering the implications for ambition and equity of extending the current approach to the land sector within the post-2020 regime.

Our analysis relies upon 21 semi-structured interviews conducted during 2015 (in person during UNFCCC negotiating sessions, or by Skype and telephone) with 14 land-use negotiators (seven from developing countries and seven from developed countries), three representatives of non-governmental organizations, and four academics/experts. Interviewees were selected based on their involvement or familiarity with land-use negotiations and to reflect a range of views. All interviewees were guaranteed anonymity and hence are only identified here by broad professional affiliation and geographical region. We also draw upon our own observation of multilateral climate negotiations, from the Lima meeting in December 2014 to Paris in December 2015, as well as intersessional negotiations, encompassing six sessions. Finally, we rely on an extensive review of primary and secondary sources, including country submissions to the UNFCCC during 2014-2015 culminating in the Paris Agreement,[3] grey literature, and existing academic analyses.

2 Governing by expertise: accounting as a site of politics

The politics of expertise, i.e., the "selective use of expert knowledge by political elites to gain support for their pre-defined policy agendas" (Fisher 1990, 28, paraphrased in Lövbrand 2009, 404–405), has been a long-standing object of critical science studies scrutiny, including in the climate domain. Lövbrand (2009) in particular has explored in detail what she terms the "links between knowledge-making and decision-making authority" in multilateral climate negotiations on terrestrial sources and sinks of greenhouse gases. Such interlinkages are now routinely analyzed within the paradigm of "co-production," which refers to a dialectical process whereby knowledge making is constitutive, insofar as it constructs particular social realities, even as a given social order shapes the nature and

[2] By lack of environmental integrity, we mean a discrepancy between what is accounted for, and what the atmosphere sees.

[3] Specifically, we analyzed all country submissions made between January 2014 and June 2015 on "elements for a 2015 agreement" to Workstream 1 of the Ad Hoc Working Group on the Durban Platform (ADP) for references to land-use (encompassing 43 submissions).

prospects of such knowledge making and its (selective) legitimation (Jasanoff 2004, see also Beck 2015; Fogel 2005).

For our purposes here, we view accounting as such a site of co-production. Viewed through a *governance* lens, we further conceptualize co-production as the twin processes of *governing* (i.e., *disciplining*) *expertise* and governing *by* expertise. These terms build on two much analyzed phenomena within science and technology studies: the politicization of science and the scientization of politics (Jasanoff 1998; Weingart 1999; Sarewitz 2004). The first, politicization of science, refers to the selective evoking of technical knowledge to further specific political interests and agendas, which we refer to here as governing expertise. Its mirror process, scientization (or technicalization) of politics, draws attention to how key morally charged and politically contested questions become translated into, and debated within, the potentially exclusionary, arcane, and technically impenetrable language of science, which may be accessible only to a select elite group of experts (see also Jasnoff 2003; Gupta 2011; Gupta et al. 2012).

In using "governing expertise" and "governing by expertise" to capture these two interrelated dynamics, our interest here is not only to show how politics and knowledge making are intertwined, but also to draw attention to the governance *outcomes* that flow from this. We do this through analyzing, inter alia, the Kyoto Protocol's LULUCF accounting rules as a site of political conflict, and how these rules have shaped the nature and scope of land-based mitigation within the UNFCCC.

3 Negotiating land-based mitigation in the current multilateral climate regime

This section analyzes the twin processes of governing (i.e., disciplining) expertise and governing by expertise, with regard to land-based mitigation within current multilateral climate governance. We discuss, first, the political decision taken within the UNFCCC's Kyoto Protocol to allow developed countries to include the land sector in meeting their mandatory emission reduction targets under this agreement and the associated crucial assumption of *fungibility* (between terrestrial and industrial emissions) accompanying this decision. We then turn to an analysis of the LULUCF accounting rules negotiated subsequent to this political decision, which impact upon the scope, scale, and manner in which land sector mitigation has been relied upon by developed countries to date.

3.1 Governing (disciplining) expertise: agreeing on fungibility

The Kyoto Protocol, adopted in December 1997, introduced legally binding emission reduction targets for developed countries for the first time. These targets were set for economy-wide industrial emissions, excluding the land sector.[4] However, the land sector was *subsequently* included under the rubric of land-use, land-use change, and forestry (LULUCF) as a means through which to meet targets on the final day of negotiations in Kyoto (UNFCCC 1997). The inclusion of LULUCF was contentious from the start, given that such inclusion had the potential to weaken commitments to reduce GHG emissions from industrial sources (Fry 2002; Schlamadinger et al. 2007). Tensions arose because of the potential for some countries to meet their Kyoto targets solely or largely through claiming significant LULUCF removals, effectively offsetting emissions from the

[4] See Annex A to the Kyoto Protocol.

industrial sector and thus relieving these countries of the need to substantially reduce industrial emissions (Lövbrand 2004).

This was evident, for example, from arguments made by some members of the so-called Umbrella Group of countries, who called for comprehensive inclusion of LULUCF.[5] As one interviewee involved in the Kyoto negotiations noted, "the Chair was told by Umbrella Group countries (US, Canada, Norway, Russia, Iceland), that there is no way we will agree [to the Kyoto Protocol] unless we can credit some land use activities."[6] The Alliance of Small Island States (AOSIS), in particular the Marshall Islands and Barbados, as well as Costa Rica and Brazil, preferred to limit reliance on terrestrial sinks or exclude them altogether (Earth Negotiations Bulletin 1997), while the European Union (EU) remained internally divided over the issue.[7]

While the details of these dynamics have been analyzed elsewhere (e.g., Fogel 2005; Fry 2002, 2007), we draw attention to two aspects below: the assumption of *fungibility* that underpins use of LULUCF to meet developed country Kyoto targets, which entailed a disciplining of scientific knowledge, and offset mechanisms negotiated under the UNFCCC and Kyoto, which also assume fungibility and implicate the land sector in *developing* countries as well.

3.1.1 Fungibility between terrestrial and industrial emissions

The conflicts over inclusion of LULUCF in the Kyoto Protocol were due in part to abiding contestations over the assumption of fungibility, i.e., the assumption that avoided emissions and removals from the land sector were interchangeable with emission reductions from fossil fuels. This assumption remained singularly contested. Brazil, for example, "wanted LULUCF completely out of Kyoto, raising all of the legitimate scientific questions about this. They didn't want any kind of cheating which was related to the accounting. In principle they thought [Kyoto] should be an energy convention, making it also about forests made it much more complicated."[8] This was also because, if included in the Kyoto Protocol, special accounting rules would be needed for LULUCF, given the unique complexities of the sector that prevented easy comparison between fossil and terrestrial emissions. As we noted earlier, land is the only sector where CO_2 is not only emitted (via forest burning and clearing and land-use change for agriculture, among other activities), but also sequestered (via photosynthesis). As such, there were a wide variety of political positions articulated at this time on *why and how* the land sector was different, and thus how valid the assumption of fungibility was.[9]

Fungibility was simultaneously much debated in scientific circles and continues to be. While some see it as unproblematic (e.g., Estrada et al. 2014; Lee et al. 2015; Parker et al. 2014), others outline key technical barriers to comparability between land and fossil

[5] The Umbrella Group is a negotiating bloc of non-EU developed countries. During Kyoto negotiations, it consisted of Australia, Canada, Iceland, Japan, New Zealand, Norway, the Russian Federation, Ukraine, and USA. Japan initially opposed inclusion of sinks, but later agreed, when under pressure to take on a higher emission reduction target (Interview with developing country negotiator, Bonn, Germany, June 9, 2015).

[6] Interview with developing country negotiator, Bonn, Germany, June 9, 2015.

[7] Ibid.

[8] Developing country negotiator, Bonn, June 9, 2015.

[9] Interviews with five developed country and seven developing country negotiators, as well as two LULUCF experts, conducted in person in Bonn, Germany, in June and October; and in Paris, France in December; and via telephone between July and October, 2015.

emissions, including inter alia, high levels of uncertainty in monitoring land-based emissions; difficulties in distinguishing between anthropogenic and natural causes of land-based emissions and removals; and non-permanence of removals (Fry 2002; Hansen et al. 2013; Mackey et al. 2013; Powlson et al. 2011).

For example, with regard to non-permanence of soil carbon sequestration, Powlson et al. have expressed concern that "the possibilities for climate change mitigation by this means may be exaggerated… even though these limitations have been clearly enunciated in numerous publications" (2011, 43–52). Fry (2002, 162) has observed that the early LULUCF discussions "lacked a critical analysis of the efficacy of sinks projects, despite the fact that…, there were a number of scientific articles questioning the efficacy of LULUCF activities." The sustained scientific critique and persisting debates around the efficacy and mitigation potential of terrestrial sinks ultimately did not impede the inclusion of LULUCF in the Kyoto Protocol, indicating that sequestration science (i.e., the science of removing emissions through terrestrial sinks) was selectively evoked by policy experts in this realm to align knowledge with a politically desired outcome—the use of sinks in climate mitigation.

3.1.2 Offsetting

The political decision to assume fungibility between terrestrial and industrial emissions also laid the basis for including land-based mitigation in developing countries within the parameters of the Kyoto Protocol. This was achieved through the Clean Development Mechanism (CDM) of the Kyoto Protocol, which allowed developed countries to partially meet their Kyoto targets by purchasing credits generated from emission reduction projects in developing countries (i.e., *offsetting* ongoing emissions in one place with reductions in another). Reliance on land-based mitigation was more limited in the CDM than under LULUCF, largely due to the sheer scale of potential credits the unrestricted inclusion of land could yield (given higher deforestation rates, and greater land areas in developing countries). Hence, "avoided deforestation" as an offsetting activity was excluded from the CDM all together, and reliance on terrestrial sinks was limited to the specific activities of afforestation and reforestation, and capped at 1 % of Kyoto targets annually (Höhne et al. 2007). This followed particular opposition to the inclusion of avoided deforestation as a crediting activity in the CDM, with Brazil, China and AOSIS raising concerns about the potential for such credits to offset an increase in developed country (industrial) emissions (Fry 2007).[10]

In 2005, a new proposal was made within the UNFCCC to incentivize avoided deforestation in developing countries (thus far excluded from the CDM). Established as a voluntary mechanism, whereby developing countries could receive financial incentives to reduce emissions from forest loss and enhance sequestration, REDD+ [11] has now been included in the Paris Agreement as a results-based payment mechanism (UNFCCC 2015, Article 5.2). Furthermore, despite current lack of clarity regarding who (the host or donor country) can credit any resultant emission reductions, REDD+ accounting rules have been developed to potentially enable REDD+ credits to be used as offsets by purchasing

[10] This point was also made in an author interview with developing country negotiator, Bonn, Germany, June 9, 2015.

[11] REDD+ refers to the agreed eligible activities in developing countries, which are: reducing emissions from deforestation and forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks.

countries or entities. This possibility has led to contentious debates within the UNFCCC over the stringency of verification required for REDD+ results (Dutschke 2013), with many developing country negotiators noting that REDD+ accounting rules are stricter than those that developed countries adhere to in crediting their own LULUCF activities.[12]

Limiting terrestrial sinks in the CDM and developing strict accounting rules for REDD+ can be seen as *political* compromises in response to concerns expressed by the EU and AOSIS, among others, over both the environmental integrity and social impacts of land-based offset projects in developing countries (Fry 2002), even as the scientific debate over fungibility has remained unchanged.

These political decisions on including land-based mitigation in the climate regime, accompanied by a selective evoking (or ignoring) of scientific disputes over fungibility, shaped negotiation of LULUCF accounting rules, to which we turn next.

3.2 Governing by expertise: accounting rules and a technicalization of politics

Once the Kyoto Protocol was agreed, along with the assumption of fungibility between terrestrial and industrial emissions, negotiations began on developing accounting rules for the land-use sector within the UNFCCC's Subsidiary Body for Science and Technological Advice (SBSTA). This technical negotiating site saw LULUCF negotiators employing complex scientific arguments about the intricacies of accounting for terrestrial emissions and removals, yet doing so in a way that suited their specific circumstances, i.e., the varying potentials in different countries for relying on land-based mitigation in meeting Kyoto targets.[13]

In analyzing these dynamics here, we review below the contested negotiations around, first, the scope and scale of permitted land-based mitigation and, second, baselines and reference levels against which to account for land-based mitigation.[14]

3.2.1 Scope and scale

Scope (i.e., *which* land-use activities were to be included) and scale (i.e., *limits* on land-based mitigation) quickly became among the most divisive issues in negotiating LULUCF accounting rules (Höhne et al. 2007; Schlamadinger et al. 2007). The Umbrella Group (in particular Canada and the USA) with large forest areas wanted a broad scope and no limits on using LULUCF to offset industrial emissions. China and the G-77, as well as AOSIS, opposed this position.[15]

The political compromise reached was to develop an accounting innovation: the *activity-based approach* to LULUCF accounting, i.e., accounting for specific land-related activities, rather than land areas. A widely asserted technical reason for this was to help distinguish between anthropogenic (i.e., managed) terrestrial emissions and removals from

[12] Several interviewees from developing countries made the point that REDD+ accounting and safeguard rules are stricter than LULUCF rules for developed countries. Interviews conducted in Bonn, Germany, June 9 and 11, and via telephone November 21, 2015.

[13] Author interviews with several developing country negotiators, in Bonn, Germany, June 9, 11, and October 21, 2015. See also Fry (2007) and Lövbrand (2009).

[14] An exhaustive account of all land-use accounting rules is beyond the scope of this paper. For comprehensive discussion of land-use rules see also, e.g., Estrada et al. (2014), Höhne et al. (2007), Iversen et al. (2014), Parker et al. (2014), Schlamadinger et al. (2007).

[15] Interview with developing country negotiator, Bonn, Germany, June 9, 2015.

natural carbon fluxes. Once an activity-based approach was selected, however, another key axis of conflict became whether all land-related activities were to be mandatory or whether countries could choose which ones (if any) to rely upon in meeting their Kyoto targets. Countries negotiated extensively on this, with the political implications of these choices obscured by technically complex discussions of GHG fluxes associated with each designated activity. Eventually, only the activities of *forest clearing* and *forest planting* (since 1990) were declared to be mandatory to account for. Countries could choose whether or not to account for other land-use activities, including *forest management*, which is potentially a large source of both emissions and removals (Ecosystems Climate Alliance 2009).

While some existing analyses of this negotiated division between mandatory and voluntary activities for LULUCF accounting emphasize the technical rationales underpinning them (e.g., Höhne et al. 2007; Schlamadinger et al. 2007), others point to the political contestations underlying these decisions (e.g., Fry 2002, and Lövbrand 2009). In particular, the decision to characterize forest management as a voluntary activity became one of the most heavily criticized aspects of LULUCF accounting rules in the Kyoto Protocol's first commitment period (2008–2012), given significant under-reporting of forest-related emissions that became possible as a result (for details, see Daviet and Goers 2009).

In addition to deciding on which activities to include, LULUCF accounting rules also addressed limits on the use of terrestrial sources and sinks (i.e., the scale of permitted inclusion). As one developing country negotiator put it, "If you set the bar too high (i.e., with strict limits on inclusion), (countries) will not participate and you get nothing. If the bar is too low, you do not reduce emissions. It is very hard to balance."[16] The key concern was that in the absence of limits, the scale of land sector emissions and removals could outweigh efforts to reduce industrial emissions (Höhne et al. 2007). While this was widely recognized, the withdrawal of the USA from the Kyoto Protocol in 2001 ironically strengthened the hand of other Umbrella Group countries in securing more widespread reliance on land-based mitigation within Kyoto, given the need to keep these countries on board (Fry 2002; Lövbrand 2009).

With the discussion on scale and limits remaining heated, the EU eventually called for caps ("allowable limits") on LULUCF use by each Kyoto Party, as a compromise. As one developed country negotiator put it, "When you're really uncertain [about your accounting rules] the political solution is to put a cap."[17] While AOSIS countries demanded an in-depth scientific analysis of proposed caps, given the collective potential of such caps to meet more than half the Kyoto Protocol's overall emission reduction target (den Elzen and Lucas 2003; cited in Höhne et al. 2007), political expediency saw little such analysis. The compromise reached was for countries to politically negotiate their own cap on LULUCF, which had the effect of generating substantial credits that countries could use in meeting their Kyoto targets.

3.2.2 Baselines and reference levels

How negotiation of LULUCF accounting rules serves as a site of political conflict was also evident in debates around the *baselines* against which to assess terrestrial emissions and removals in a given period. Agreeing on baselines is substantially more complex for the land sector than it is for industrial emissions, given that land is the only sector with emissions as well as removals. Industrial emission reductions are straightforwardly

[16] Interview with developed country negotiator, Bonn, Germany, June 10, 2015.

[17] Interview with developed country negotiator, Bonn, Germany, June 6, 2015.

assessed through a gross–gross baseline approach, wherein emissions in a base year are compared with emissions in the reporting period (Rocha et al. 2015). However, inclusion of emissions and removals in the same accounting framework requires, logically, a net–net approach.[18] A net–net approach, i.e., comparing emissions minus removals in the base year against emissions minus removals in the reporting period, would maintain the symmetry of the gross–gross approach (Rocha et al. 2015; Schlamadinger et al. 2007). While scientifically tenable, the political challenge of using a net–net approach, however, is that any *increase* in emissions from the land sector in the reporting period would make targets more difficult to meet.[19] This possibility is exacerbated by the fact that forest management decisions of the past determine whether managed forests are a net source or a net sink during any given period (referred to as legacy effects), leading to most countries with Kyoto targets refusing to accept a net–net accounting approach.[20]

Given this opposition to net–net accounting, a much more complex approach to baselines for the land sector was negotiated: the "gross-net" accounting approach. This does not include emissions and removals from forest-related activities in the baseline, which reflects only industrial emissions, but does allow for both industrial and (selected) forest-related activities to be accounted for during the subsequent reporting and commitment period (Iversen et al. 2014). The gross-net approach is favoured by those countries with an overall forest sink (i.e., where terrestrial removals are higher than terrestrial emissions in a commitment period), making overall targets easier to meet. As a result, it has been criticized for permitting unearned or "windfall" credits (Daviet and Goers 2009; Rocha et al. 2015) for such countries.

The gross-net approach was, however, *not* supported by countries where the forest sector is an overall source of emissions (i.e., where emissions from deforestation are higher than removals through forest planting), given that these emissions would then be added to overall targets, making them harder to meet (Rocha et al. 2015). As one negotiator put it, "…if you have any kind of rule which is just—deforestation is really bad, you have to debit it—then straight away any country with high deforestation is going to have very high emissions under that accounting framework."[21] However, very few developed countries have high deforestation rates (Australia being a notable exception[22]), making the decision to have a gross-net LULUCF accounting approach for Kyoto politically feasible. It proved, furthermore, to be a boon for those countries (including in the EU) with low deforestation rates *but* with intensive forest management, given that forest management was a voluntary activity that could be excluded from consideration in meeting first commitment period Kyoto targets.

The contested process of negotiating politically palatable (but also scientifically defensible) baselines continued for the second commitment period of the Kyoto Protocol (2013–2019). One key change was that forest management became a mandatory activity

[18] This point was made in several interviews, including with a developed country negotiator, Bonn, Germany, June 11, a LULUCF policy expert via telephone June 16, and an NGO representative in Paris, France December 9, 2015.

[19] Interview with developed country negotiator, Bonn, Germany, June 11, 2015.

[20] However, a net–net approach is accepted for cropland and grazing lands, where carbon stocks can be affected in short time periods through management practices (Schlamadinger et al. 2007).

[21] Interview with developed country negotiator, Bonn, Germany, June 11, 2015.

[22] As a result, Australia negotiated a special clause in the Kyoto Protocol (Article 3.7), allowing it to apply net–net accounting to deforestation (otherwise only applied to cropland and grazing land management), resulting in significant windfall credits as deforestation rates dropped from historical highs (Macintosh 2011).

for the Kyoto second commitment period, following intense NGO lobbying to close "LULUCF loopholes."[23] With this, however, the EU, together with some Umbrella Group countries, insisted on revisiting the gross-net baseline accounting approach *for the specific activity of forest management* in the Kyoto second commitment period, once it became mandatory to include.

With the flexibility to exclude this activity now removed, and the accounting benefits that this flexibility had earlier conferred now gone, the EU called for forest management not to be subject to a gross-net baseline, but rather for development of a so-called Forest Management Reference Level (FMRL) (Iversen et al. 2014[24]). The use of *reference levels* is another unique accounting innovation in this context, developed as a political compromise between those trying to improve the credibility of accounting rules and those wanting to maintain flexibility in use of LULUCF to meet targets.

The FMRL means that instead of a baseline against which to judge performance in a given period, countries can propose a quantified (expected) future level of performance (in terms of net emissions from forest management) and compare this against actual emissions at the end of a commitment period (Rocha et al. 2015). Known as a "projected reference level," the FMRL was seen by the EU as crucial to avoid the problems of legacy effects associated with forest management, but was also subject to a cap to avoid excessive credits. However, any use of reference levels opens up the possibility of inflating future expectations of emissions, in order to make targets easier to meet. As one developed country negotiator put it, "The projected reference level is the most politically feasible [accounting approach] to agree on, there are problems with it, but the alternatives also have problems. [It is] used for political agreement."[25]

It is also important to note here, in concluding, that the REDD+ mechanism also relies on reference levels (rather than baselines) in assessing performance, allowing countries to set business-as-usual (BAU) expectations for increases in deforestation and to receive credits for any improvement against these BAU expectations. The credibility of the reference level approach is heavily reliant on technical review (Briner and Konrad 2014). Yet reviews remain fraught with challenges, given extensive scientific uncertainties and varying political expectations. Analysis has shown that the level of credits from LULUCF varies widely depending on plausible interpretations of accounting rules (Böttcher and Graichen 2015).

The discussion above shows how the inclusion of land-use to date in the multilateral climate regime reflects politically negotiated compromises, despite the ostensibly technical character of LULUCF accounting rules. One dominant response to perceived LULUCF "loopholes" has been to advocate improved rules and increased ambition through ensuring that negotiations are "based on sound science," with greater reliance on data sets to assess the impact of various options (Höhne et al. 2007, 354). Yet, the reality that "LULUCF is a negotiated system that tries to work around competing national interests"[26] goes against the notion that "sound" science-based rules, seen as credible by all on the basis of their

[23] From interview with NGO representative, Paris, France, December 8, 2015.

[24] Iversen et al. point to the mandatory inclusion of forest management as one of the reasons behind the FMRL; interviews with country negotiations in Bonn, Germany, June 9 and October 21, as well as an NGO representative in Paris, France, December 9, also raise this issue.

[25] Interview with developed country negotiator, Bonn, Germany, June 6, 2015.

[26] Interview with developed country negotiator, Bonn, Germany, June 6, 2015.

technical merits, can be devised. As one negotiator put it, "there is no perfect rule—what seems fair to one is an extra burden for another."[27]

As several interviewees have also noted, however, country-specific data on land-use emissions have improved as a result of requirements for LULUCF accounting, with one land-use expert adding that "except in a few countries, fears of LULUCF credits swamping Kyoto targets did not materialise."[28] This notwithstanding, our discussion highlights how LULUCF was introduced into the Kyoto Protocol to make developed country emission reduction targets easier to meet. Through political negotiations and compromise, complex accounting rules were designed to both permit and limit the degree to which terrestrial sinks could be used to offset industrial emissions.

In a post-2020 climate regime, where land is expected to play a more prominent role, any approach to mitigation that focuses on "net" emissions (i.e., emissions minus removals), while obscuring the politics hidden in land-use accounting, runs the risk of not delivering the required ambition and potentially exacerbating inequitable burden sharing. We turn to these issues next.

4 Negotiating land-based mitigation in the Paris Agreement

The architecture of the post-2020 climate regime differs from that of the Kyoto Protocol. In contrast to having multilaterally negotiated emission reduction targets for countries, the overall ambition level is agreed multilaterally in the Paris Agreement through the temperature goal (Article 2.1) and the long-term mitigation goal (Article 4.1) (UNFCCC 2015). In seeking to further these goals, the Paris Agreement institutionalizes two key elements: a bottom-up process whereby each country develops its own "nationally determined contributions" (NDCs) to meeting these aggregate goals, which may include land-based mitigation, and a multilaterally agreed "transparency framework"[29] through which to account for, and report on, the progress that countries are making toward implementing their NDCs.

As in the previous section, we proceed here by first analyzing the dynamics of governing (i.e., disciplining) expertise that might be discernible in how the land sector is implicated in the Paris Agreement, with a focus on the long-term mitigation goal. Second, we consider the current state of debate regarding *accounting* for land-based mitigation in the Paris Agreement. Here, we touch briefly upon divergent views over whether a common accounting framework is required for all countries and associated debates over whether such a common framework requires countries to take on quantified targets, including for the land sector. Through doing so, we illustrate the implications of continuing to rely on a "governing by expertise" approach to land-based mitigation (and its accounting rules) in the post-2020 era.

[27] Interview with developed country negotiator via telephone, October 13, 2015.

[28] Interview with LULUCF expert via telephone on June 21, 2015. Other interviews, with a developed country negotiator in Bonn, Germany, June 10, and a LULUCF expert in Paris, France, December 11, also made this point.

[29] In our discussions below, we focus on accounting issues, rather than on the broader negotiations around a (common) transparency framework in a new agreement. For an analysis of the contested geopolitics of transparency in global climate governance, see Gupta and Mason (2016).

4.1 Governing (disciplining) expertise: land-use and the long-term mitigation goal

Analyzing the prospects for a disciplining of expertise in the manner in which land is implicated in the Paris Agreement requires consideration of the long-term mitigation goal articulated within it. Negotiations on language to capture aggregate mitigation ambition were long and intense, in the lead up to finalization of the agreement in Paris. Terminology such as "net-zero emissions," "near zero," carbon or climate neutrality, and decarbonization all appeared in the draft text during the course of the negotiations. A mitigation goal of "net-zero" emissions was particularly contentious, with some seeing this as a straightforward scientific statement on an approach to stabilizing atmospheric GHG emissions,[30] while others viewed it as a political license to "offset industrial emissions with land-based sinks."[31]

The net-zero language was introduced to the UNFCCC discussions after the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report included long-term mitigation pathways that relied heavily on assumptions of "negative emissions" (meaning the removal of carbon from the atmosphere via terrestrial sinks, often combined with geological storage) (IPCC 2014). It was first raised during the Lima climate meeting in December 2014, where New Zealand suggested a mitigation goal of "net-zero CO_2 emissions by 2100 in line with the latest science."[32] Such a position received vocal support from Switzerland,[33] but Brazil noted that by ascribing "the latest science" a legal role in the official text "we might be creating some politicization."[34] Bolivia, Argentina, and Ecuador opposed the use of "net-zero" on the grounds that it introduced a new concept that did not appear in the Framework Convention, or in related decisions.[35] Norway and the EU supported the terms carbon or climate neutrality,[36] and the USA preferred "decarbonisation of the global economy" (Ajit 2015a).

With no consensus emerging, the ambiguous language that became the long-term mitigation goal in the Paris Agreement calls for a "peaking of greenhouse gas emissions… as soon as possible" (i.e., without identifying a specific time frame, or a specific limit on emissions) to be achieved through "a balance between anthropogenic emissions by sources and removals by sinks" (UNFCCC 2015, Article 4.1). The term "removals by sinks" leaves open the possibility of continuing industrial and terrestrial emissions, as long as these are (ostensibly) being offset by enhancement of sinks.

It is important to note here that the wording of this long-term mitigation goal is very close to the contentiously negotiated paragraph on inclusion of land-use in the Kyoto Protocol, which refers to "net changes in greenhouse gas emissions *by sources and removals by sinks*" (UNFCCC 1997, Article 3.3, italics added). A key difference is that the Kyoto Protocol defines the use of sinks as "limited to afforestation, reforestation and

[30] Author interview with LULUCF expert, Paris, France, December 8, 2015.

[31] Interview with NGO representative, Bonn, Germany, October 20, 2015.

[32] Author personal observation, COP 21 Lima, December 6, 2014.

[33] Author personal observation, Geneva, February 8, 2015.

[34] Ibid.

[35] These points were raised frequently by these countries and were observed during open meetings on the long-term goal during the September 2015 negotiating session in Bonn, Germany.

[36] The position of the EU and Norway on the long-term goal changed throughout the year, from supporting net-zero in the Bonn September session to calling for carbon and climate neutrality during the Paris negotiations, as an alternative to the opposition from developing countries on net-zero (author observations; see also Ajit 2015a).

deforestation since 1990" (UNFCCC 1997, Article 3.3), which circumscribes and limits the activities that qualify as "removals by sinks." A second key difference is placement and context. Article 4.1 in the Paris Agreement is the collective long-term mitigation goal, while the mitigation goal in the Kyoto Protocol reads, "Parties shall limit the emissions of the greenhouse gases listed in Annex A" (which refers to energy and industrial emissions, excluding terrestrial emissions) to "not exceed their assigned amounts" (UNFCCC 1997, Article 3.1), thus, with a clear focus on reducing emissions from fossil fuel use.

Reliance on land-based mitigation in the Kyoto Protocol was introduced *after* targets for industrial emission reductions were set (as discussed in Sect. 3), and was limited from the start (although the precise nature of these limits remained the subject of political debates). In the Paris Agreement, on the other hand, land-based sinks have moved from being a politically contested add-on to occupying center stage in the long-term mitigation goal, as laid down in Article 4.1.

But why exactly does Article 4.1 of the Paris Agreement implicate land, and to what extent might this reflect a governing (or disciplining) of expertise, with implications for environmental integrity and ambition? "Balancing emissions and removals" effectively means the same as "net-zero emissions," carbon neutrality, and similar terminology (Levin et al. 2015), which all imply that terrestrial sinks are both fungible with, and will be used to offset, ongoing (industrial and terrestrial) emissions (Schaeffer et al. 2013).

So while a goal that essentially puts the world on a pathway toward net-zero global emissions appears ambitious, Article 4.1 says nothing about the *scale* of reliance on land-based mitigation that would be required to meet this global mitigation goal, nor the speed and timing of a concurrent reduction in fossil fuel use, hence obscuring political questions around when, how and by whom emissions are reduced. Going beyond this, and of direct relevance to the governing (disciplining) of expertise, the varied scientific uncertainties and contestations around the sequestration potential and permanence of terrestrial sinks, as debated during the Kyoto period, remain salient for the Paris Agreement, leaving open the prospect that scientific expertise will (continue to be) selectively evoked in justifying specific efforts at "balancing emissions and removals" in the decades to come.

4.2 Governing by expertise: technicalizing (politics of) land-use accounting?

With the land sector set to play a crucial and open-ended role in future climate mitigation under the Paris Agreement, a politically charged question is how *accounting* for this sector will occur in the post-2020 climate mitigation era, whether a *common* accounting framework is required for all countries, and if this requires countries to take on *quantified* targets, including for the land sector. These debates are linked in turn to overarching conflicts over differentiation in obligations between developed and developing countries, in an agreement that is "applicable to all."

During negotiation of the Paris Agreement, the EU and the USA took the position that the purpose of a common accounting framework was to permit comparability, which in turn required quantified targets (Ajit 2015b). Whether all countries should provide quantified targets thus became, and remains, a particularly contentious issue, tied up with fundamental conflicts over whether inclusion of the land sector in NDCs is to be voluntary or mandatory and also whether the land sector can be included in any new market mechanisms (established via Article 6 of the Paris Agreement).

Throughout the negotiations, countries proposed a variety of approaches to mitigation commitments, ranging from quantified economy-wide emission reduction targets (e.g.,

EU[37] Switzerland,[38] Norway[39]); a diversity of mitigation actions for developing countries, including emissions intensity targets (China[40]); and commitments to qualitative policies and measures (Nepal[41]). This debate has particular relevance for the land sector, due to the difficulty of quantifying land sector emissions and the complexity of including these in an accounting framework that includes industrial emissions, as discussed in Sect. 3.[42]

The Paris Agreement leaves discussions of a (common) accounting framework and specific rules for land-use accounting, to future negotiations.[43] We provide here (in Table 1) a brief overview of a few *intended*[44] NDCs (INDCs) proposed by countries in the lead up to the Paris meeting, in order to reveal the diversity of approaches currently being adopted to land-use (and land-use accounting) in the context of the Paris Agreement, and to the scope and scale of such inclusion.[45]

Table 1 provides a glimpse into the political conflicts that are likely to come to the fore in determining (and accounting for) the contribution of the land sector to countries' mitigation commitments. As a developed country negotiator noted about the politically contested nature of land sector accounting, "…in the context of a new agreement, capacities of countries are more diverse, so this adds more complexity to the idea of a common framework [for land-based mitigation]. It is difficult to find common accounting rules that suit all… sinks have evolved differently in different countries, leading to fighting over accounting rules to suit national circumstances."[46]

The diversity of country circumstances in the land sector also complicates the idea of comparability of effort. A recent comprehensive assessment of countries' INDCs by Grassi and Dentener (2015) indicates a potential LULUCF mitigation contribution of 20–25 %, relative to other sectors, by 2030. This implies that the land sector is expected to be a significant component of mitigation efforts in the future, even as the authors note large uncertainties in these estimates "due to *countries projections* and *accounting rules*" (Grassi and Dentener 2015, 13, italics in original). The INDC Synthesis Report, produced by the UNFCCC Secretariat, further adds that "several of the INDCs do not provide comprehensive information on the assumptions and methods applied in relation to LULUCF, which presents a major challenge for the quantitative evaluation of the aggregate effect of the INDCs" (UNFCCC 2016, 6).

[37] *The Ad Hoc Working Group on the Durban Platform for Enhanced Action (ADP): the 2015 Agreement.* Submission by Italy and the European Commission on behalf of the European Union and its Member States. Rome, October 14, 2014.

[38] *Elements of the 2015 Agreement: Switzerland's views,* March 4, 2014.

[39] *Norway submission to the ADP,* March 6, 2014.

[40] *Views and proposals on the work of the Ad Hoc Working Group on the Durban Platform for Enhanced Action.* Submission by Nepal on behalf of the Least Developed Countries Group, March 17, 2014.

[41] *China's submission on the work of the Ad hoc Working Group on Durban Platform,* March 6, 2014.

[42] Multiple interviewees emphasized capacity constraints facing developing countries, including three developed and seven developing country negotiators, one policy advisor, and one NGO representative, interviews undertaken in Bonn, Germany, June 6-11; by telephone July–October, and in Paris, France, December 11, 2015.

[43] Paragraphs 31, 37, 38 of Decision 1/CP.21 contain mandates for further negotiations to develop accounting rules (UNFCCC 2015).

[44] In 2015, countries submitted *intended* NDCs, which are expected to become NDCs when the Paris Agreement enters into force in 2020.

[45] It is outside the scope of this paper to analyze all submitted INDCs; our discussion here is illustrative, rather than comprehensive.

[46] Interview with developed country negotiator, Bonn, Germany, June 10, 2015.

Table 1 Overview of land-use inclusion in selected INDCs

Country	Mitigation commitment	Land-use inclusion	Observations
Australia	26–28 % below 2005 by 2030	Included in economy-wide target. Net–net accounting based on inventory reporting	IPCC guidance for natural disturbance and variation
EU	At least 40 % below 1990 by 2030	Included in economy-wide target, but accounting rules are yet to be established	Inclusion of LULUCF may weaken 40 % target, depending on accounting rules used
Mexico	Unconditional target of 25 % (conditional pledge of up to 40 %) below BAU by 2030	0 % deforestation by 2030 included as an adaptation measure	Conditional pledge will require market mechanisms; no reference to accounting rules
New Zealand	30 % below 2005 by 2030	Included in economy-wide target and will build on Kyoto Protocol rules	Provisional target pending approaches taken to land sector accounting and access to carbon markets
Norway	40 % below 1990 by 2030	Included in economy-wide target, but accounting rules dependent on EU decisions	Inclusion of land sector and subsequent accounting rules shall not reduce 40 % target
Russia	25–30 % below 1990 by 2030	Included in economy-wide target	Significant uncertainty around accounting assumptions for land-use sink
US	26–28 % below 2005 by 2025	Net–net accounting for land sector	Notes methodological challenges to estimating emissions in land sector

Based on author analysis of selected INDCs submitted in 2015 that included the land sector

The diversity of country circumstances and approaches, as demonstrated in INDCs, points to the difficulty of having a common accounting framework for the land sector, which is highlighted in the politics of deciding upon baselines or reference levels for terrestrial emissions. Some countries argue that common accounting rules for all would be feasible, including for the land sector, *as long as* flexibility exists to set land-based mitigation reference levels appropriate to national circumstances.[47] As one developed country LULUCF negotiator pointed out, "the key point is having the flexibility to set appropriate baselines, and I think a lot of developing countries don't realize that [by doing so] they could bring their whole land sector in and set baselines that create an expectation of zero debits, zero credits."[48] This implies, however, that flexible accounting rules might come to be seen as a means for countries to report net-zero emissions, rather than as a means by which to facilitate emission reductions. While flexibility in the setting of reference levels and/or baselines (to accommodate whether land is a net source or net sink of emissions for a given country at any given period of time) would be a politically plausible way for developed and developing countries, with radically different land-use scenarios, to agree to common accounting rules for the land sector, such an approach would obscure real emissions from this sector.

[47] Interview with developed country negotiator, Bonn, Germany, June 11, 2015.

[48] Ibid.

More generally, this highlights the inadequacy of a "governing by expertise" approach to addressing the social and political questions inherent in the role of land in moving toward a zero-carbon future. Rather than technicalizing what are fundamentally political conflicts, future discussions on the scale, scope, and accounting approaches to land-based mitigation face the challenge of how to reveal and engage with, rather than obscure, the political choices and trade-offs therein.

5 Conclusion: breaking new ground or allowing history to repeat?

In the recently negotiated Paris Agreement, land-based mitigation has moved from an earlier marginal and contested role in multilateral climate politics to center stage. This is in large part due to the assumed reliance on "negative emissions" in the second half of the century, introduced into the debate through IPCC mitigation scenarios (IPCC 2014) and now implicated in the long-term mitigation goal. As we have shown here, (over)-reliance on land-based sinks could have far-reaching political consequences, given the likely distributional impacts of land-based mitigation, and concerns over fungibility in using terrestrial sinks to offset industrial emissions. Furthermore, accounting rules for the land sector remain a crucial site wherein the level of ambition in the new agreement, and allocation of responsibility and burden sharing among countries, will be negotiated.

The current state of play on these issues is that the Paris Agreement sets no direct limits on "balancing" emissions with removals, although it does say that the "balancing" must be done "on the basis of equity," and "in the context of sustainable development and poverty eradication" (UNFCCC 2015, Article 4.1). This notwithstanding, in a context where removals via terrestrial sinks are expected to make a significant contribution to achieving the long-term mitigation goal, this implies a need for land to shift, eventually, from being a *net source* globally to a *net sink*. Yet the distributional consequences of this remain crucial to analyze, with existing models "universal[ly] projecting that the majority of agriculture and forestry mitigation, and bioenergy primary energy, will occur in developing and transitional economies" (IPCC 2014, 68). With this in mind, our analysis reveals the need for a more open political debate over diverse mitigation pathways and their implications over the course of the century, one which takes into account the social and environmental limits to land-based mitigation. Negotiating limits to land-based mitigation that consider not only the technical, but also the political, socioeconomic *and* equity aspects is necessary, in determining how much, where, and what type of land-based abatement can reasonably be relied upon for climate mitigation.

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Chapter 5

The future of land-based mitigation in global climate modelling

The previous chapter showed how land-based mitigation is now central to global climate governance, with the 2015 Paris Agreement placing removal of carbon-dioxide via terrestrial sinks at the center of its long term mitigation objective. The conclusion to the previous chapter raises the concern that "(over)-reliance on land-based sinks could have far reaching political consequences", given projections that the majority of land-based mitigation would occur in developing countries (Dooley & Gupta 2017, p.498). In this chapter I explore these consequences further, by assessing the scale of projected reliance on land in 2 °C and 1.5 °C scenarios, and the co-production of science and policy that both engenders and renders credible these projections.

With science as an institution at the heart of global climate governance, climate models have been documented as resting at the heart of climate science (Miller & Edwards 2001a). Miller and Edwards chart the relationship between computer models and climate politics, demonstrating the fundamentally normative and political, as well as scientific, implications of model-based knowledge (Miller & Edwards 2001b). The rules, discourses and cultures of institutions around climate science and climate modelling set the context of what does and does not count as valid knowledge for climate governance (Edwards 2001). However the technology and energy futures depicted by integrated assessment models are increasingly being scrutinized both in the academic literature (Anderson & Peters 2016; Stern 2013; Beck & Mahony 2017; Anderson 2015b; Geden 2015) and the popular press (Martin 2017; Harvey 2018; Velasquez-Manoff 2018). Here I provide a more systematic scrutiny, comparing modelled outcomes of land-based mitigation to sustainability limits derived from the literature.

This chapter consists of two sections, which cover a range of modelled mitigation scenarios compatible with the Paris Agreement. Section 5.1 presents a paper published in the journal *Global Sustainability* in 2018 that assesses the level of bioenergy demand and extent of land-use change in modelled mitigation pathways compatible with limiting warming to well below 2 °C. These pathways are taken from the recent generation of IAM scenarios harmonized under a set of policy and developmental assumptions known as the Shared Socio-economic Pathways (SSPs). This section then uses content analysis via interviews and documents to comment on the ways in which these pathways are co-produced between scientists and policy-makers, and the implications of this for objectives related to food security and biodiversity.

Section 5.2 then looks at more recently published scenarios under the SSP framework for pathways compatible with limiting warming to 1.5 °C. These scenarios show similar levels of bioenergy demand and land-use change, raising similar concerns over impacts of land-based mitigation on sustainable development as was found in Section 5.1. However, a handful of scenarios which limit warming to 1.5 °C while excluding or minimizing reliance on bioenergy have now been published. These scenarios show that alternative mitigation options are available, and highlight the role of science in society as one of providing policy alternatives and highlighting, rather than obscuring, the choices facing society.

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5.1 Co-producing climate policy and negative emissions: trade-offs for sustainable land-use

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Non-technical summary. Under the Paris Agreement, nations have committed to preventing dangerous global warming. Scenarios for achieving net-zero emissions in the second half of this century depend on land (forests and bioenergy) to remove carbon from the atmosphere. Modelled levels of land-based mitigation could reduce the availability of productive agricultural land, and encroach on natural land, with potentially significant social and environmental consequences. However, these issues are poorly recognized in the policy-uptake of modelled outputs. Understanding how science and policy interact to produce expectations about mitigation pathways allows us to consider the trade-offs inherent in relying on land for mitigation.

Technical summary. Science enables better understanding of climate change causes and impacts but may also define the 'climate problem' in technical terms, with technical solutions, as seen in the recent inclusion of negative emissions technologies (NETs) in Integrated Assessment Models (IAMs) to meet the Paris Agreement's temperature goals. This paper examines the sustainability of land-based carbon removal, using a co-production lens to explain the legitimization of NETs as key mitigation options. We evaluate the scale of NETs in the most recent generation of <2 °C scenarios, finding that projected levels of land-based mitigation imply strong trade-offs with other societal goals. Future demand for bioenergy from dedicated cropland drives large-scale land-use change across all models. Upper ranges of modelled outputs would require up to a doubling of global cropland, with potential losses of up to a quarter of both current pasture and natural lands by 2100. We find that the perception of model-based knowledge as 'objective science' lends authority to outcomes that might otherwise be more critically debated and contested. Closer engagement between modellers and policy experts for mitigation scenario development would allow for more negotiated forms of knowledge production that might better clarify and represent the multiple objectives and interests at stake in the utilization of limited land resources.

1. Introduction

Under the 2015 Paris Agreement the international community has committed to holding global average warming to well below 2 °C above pre-industrial levels and to pursue efforts to limit warming to 1.5 °C (Art. 2.1[a]) [1]. A key challenge for the Agreement is the stated intention to achieve this goal "in the context of sustainable development and efforts to eradicate poverty" (Art. 4.1) and "in a manner that does not threaten food production" (Art.2.1[b]) [1].

Modelled pathways using Integrated Assessment Models (IAMs) are increasingly relied upon to define mitigation scenarios. Most IAM scenarios compatible with the Agreement's temperature goal factor in significant use of negative emissions technologies (NETs) to remove CO_2 from the atmosphere [2]. This accords with the objective to achieve a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" (GHG) (Art.4.1) [1]. IAM scenarios assume these removals will be achieved through land-based NETs – afforestation and bioenergy with carbon capture and storage (BECCS) [3] – measures that require appropriating extensive areas of land.

Questions surround the feasibility of large-scale land-based carbon removal, given the potential impacts of increased land demand on food security and biodiversity [3–5]. The social and environmental implications of such measures have not yet been fully assessed [4,6]. However, the technology and energy futures depicted by IAMs are increasingly being scrutinized [2,7,8]. There is growing concern that IAMs may offer an unrealistically high estimate of the potential for land-based NETs. This in turn could serve to mislead policymakers into believing that rapid emission reductions can be delayed, creating a 'lock-in' situation where dependence on NETs can no longer be avoided after exceeding the carbon budget [4,9,10].

It is in relation to these concerns that this paper evaluates the latest generation of scenarios for limiting warming to below 2 °C, harmonized under a set of policy and developmental assumptions known as the Shared Socio-economic Pathways (SSPs) [11]. We take three

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already agreed and potentially competing societal goals enshrined in the UN Sustainable Development Goals (SDGs) as relevant markers of global objectives reliant on land [10]: not threatening food production (SDG 2), biodiversity protection (SDG 15) and climate action (SDG 13). We assess the sustainability of land-based carbon removals intended to mitigate climate change according to these three objectives, by comparing IAM outputs to literature related to food production and biodiversity goals.

Finding that the amount of land used for mitigation in IAM outputs in 2100 exceed reported constraints to protect food production and biodiversity, we consider how land-based NETs have been legitimized as key mitigation options in IAM scenarios. The concept of scientific co-production [12] illuminates how knowledge is developed and gains authority at the science–policy interface. We ask how model-based knowledge is co-produced with policy demands, and to what extent political choices inherent in the production of IAM scenarios may be obscured by scientific framings.

Section 2 outlines the analytical framework of co-production and provides a background on climate models in general and IAMs in particular, reviewing existing analyses of how these models came to inform climate policy. Section 3 describes the methodology used to analyze relevant data from IAMs, and to gather views from modellers and experts in the field. In section 4 we assess the sustainability of land-based carbon removal in light of food production and biodiversity goals. Section 5 examines how model-based knowledge is co-produced with policy demands and considers how land-based NETs have been legitimized as key mitigation options in IAM scenarios. Section 6 concludes that systematic negotiation between knowledge makers and knowledge producers could offer more policy-relevant results based on open debate of the social values and their trade-offs embedded in models.

2. Co-production and climate modelling

2.1. Co-production of knowledge

While in public policy the term 'co-production' often refers to an iterative process of top-down and bottom-up decision-making [13], in this paper we use the term in the context of Science and Technology Studies (STS), as an analytical tool to understand the process of scientific knowledge production [14]. This approach highlights the engagement between science and politics, in which science is seen neither as an objective truth, nor as only driven by social interests, but as being co-produced through the interaction of natural and social orders [12].

Jasanoff has distinguished science for policy-making as 'regulatory science', which "straddles the dividing line between science and policy" (p. 14 [15]), as scientists and regulators try to provide answers to policy-relevant questions [12]. Distinct from pure 'research science', regulatory science represents a negotiated and constructed model of knowledge production, where boundary-work (maintaining sharp boundaries between facts and values) is critical to the authority of scientific knowledge. By contrast, Jasanoff suggests that more robust outcomes are achieved when scientists and policymakers share the responsibility of providing the 'best answers' to difficult questions. Jasanoff has termed this 'serviceable truth' – a state of knowledge that satisfies tests of scientific acceptability and supports reasoned decision-making [15].

Co-production views scientific endeavours as constitutive and/or interactional [12,16]. While constitutive approaches to co-production often focus on emerging technologies and knowledge, interactional approaches look at points of knowledge conflict and resolution within existing structures and institutions to identify the normative dimensions of expertise [12]. Here we will focus on what we see as knowledge controversies around the scale of NETs in IAM mitigation pathways. We will examine the interactional aspects of co-production between climate modellers and policymakers to explain how model results are produced, gain authority and are institutionalized in the policy process.

2.2. Global climate models and technocratic visions

Climate models have significantly advanced scientific understanding of future climate impacts. General Circulation Models (GCMs) are coupled atmosphere–ocean models that mathematically simulate changes in climate in response to altered boundary conditions (representing the earth's surface and atmosphere). They have evolved over time to include changes in GHG emissions levels. However, as far back as the late 1990s, Shackley *et al.* [17] questioned the policy-usefulness of GCMs because of their limitations in dealing with uncertainty. They argued that the dominance of models – widely perceived as the 'best science' available for climate policy input – leads to a technocratic policy orientation, which tends to obscure political choices that deserve wider debate.

There is now an established body of literature critiquing the implications of this expert-led modelling approach to climate policy [14,17–20]. In 2001, Demeritt retraced the history of climate modelling to reveal underlying social and epistemic commitments, unmasking how politics gets built into science, enabling a technocratic and global framing of climate change, devoid of people and impacts [18].

Demeritt suggested "a more reflexive politics of climate change and of scientific knowledge based on active trust" (p. 307 [18]). This can be likened to Jasanoff's 'serviceable truth', where the aim is not an objective verifiable truth, but a transparent and negotiated outcome of science sufficient to inform policymaking while assuring those exposed to risk that "their interests have not been sacrificed on the altar of an impossible scientific certainty" (p. 250 [15]).

2.3. Knowledge production through Integrated Assessment Models

More recent critiques [21–24] have focused on IAMs, which combine economic and social assumptions with observations from GCMs to achieve cost-optimal mitigation outcomes. IAMs minimize the economic cost of climate solutions, unless they are specifically constrained to do otherwise [25].

Initially, model-based scenarios used in climate research were developed through iterative approaches where IAMs were used to determine possible emissions pathways under a given set of assumptions about the future, with the outcomes fed into GCMs to determine warming levels [26]. Storyline narratives, such as the Special Report on Emissions Scenarios (SRES) used in the Intergovernmental Panel on Climate Change (IPCC)'s 2007 Fourth Assessment Report, were based on scenarios of future emission development trajectories, without consideration of climate policy intervention. The results from IAMs produced under SRES provided further inputs to GCMs to determine warming levels for different scenarios of possible future development, giving high and low warming outcomes [26].

Changes in the way scenarios were developed for the IPCC Fifth Assessment Report (AR5) have changed the way IAMs are used to inform climate policy. In 2008, the IPCC requested the modelling community to develop a new set of scenarios, resulting in the four 'representative concentration pathways' (RCPs) subsequently used in 2014 for AR5 [26]. Under the RCP approach, different 'target' atmospheric concentrations of GHGs corresponding to different global average temperature outcomes were established. IAMs were subsequently used to determine combinations of future policy and technology measures to produce mitigation pathways for each target atmospheric concentration.

The move from SRES to RCPs represents a critical change in how models are used to inform climate policy: from 'what climate outcomes would future emissions produce?' to 'what are the measures and actions needed to reach particular warming outcomes?'. IAMs originally designed for exploratory research were applied as decision-making tools [27,28]. The use of models had shifted from being about showing what level of emissions (and hence warming) different future development scenarios would result in, to determining what technology choices and policies are required to achieve a specific warming 'target'. This shift from predictive to determinative places IAMs in a position of considerable authority regarding future climate policy, warranting an exploration of how modelled outputs are co-produced with policy demands, and which views gain authority.

IAMs can be understood as what Jasanoff has referred to as an emerging body of regulatory science responding to societal concerns over the environment – including sustainability science, impact assessment and integrated assessment – which are framed by objective, quantified decision-making techniques [15]. Co-production allows us to examine how modellers have used notions of objectivity to enact boundaries, which are key to maintaining scientific credibility: "the creation of boundaries is critical to the political acceptability of advice" (p. 236 [15]). How objectivity is understood and institutionally embedded in political systems has implications for legitimating policy and gaining social credibility and authority, determining "whose testimony should be trusted and on what basis" (p. 29 [15]).

3. Methodology

This paper aims to examine the sustainability of land-based carbon removal in light of food production and biodiversity goals; to examine how model-based knowledge is co-produced with policy demands; and to consider how land-based NETs have been legitimized as key mitigation options in IAM scenarios. To answer the first research question, we used a quantitative analysis of SSP scenarios to identify the extent of land-use change in mitigation scenarios. For the latter two questions, we conducted semi-structured interviews with modellers and policy experts to explore the associated co-production and legitimation of model-based knowledge in climate policy.

Using the five SSPs, a new generation of IAM scenarios was made available in October 2016[i] [29]. From this set of scenarios, we used the RCP2.6 mitigation pathway, as the only pathway compatible with the 'well below 2 °C' temperature goal of the Paris Agreement at the time of analysis[ii] [29]. SSP3 is excluded because no SSP3 scenario achieved RCP2.6. Fifteen scenarios were examined from across the remaining SSPs for five models: AIM, IMAGE, REMIND-MAGPIE, GCAM4 and MESSAGE (WITCH was excluded due to incomplete datasets on land-use). Table 1 provides a summary of key land-use characteristics for each of the SSPs and shows which IAM scenarios were analyzed here.

We assessed the scale of bioenergy (measured in joules) and land-use change (measured in hectares) in RCP2.6 by examining the results for these variables for the 15 scenarios analyzed. We performed a simple comparison of model results for primary bioenergy demand in 2050 and 2100 to literature assessing sustainable bioenergy supply potentials.

We examined land-use change according to the five categories in the SSP database: urban area, cropland, pastureland, forestland (undifferentiated between plantation and natural forest) and 'other natural land' (non-agricultural and non-forested ice- and desert-free land). The extent of land-use change in mitigation scenarios was determined by comparing the difference between 2010 and 2100 for RCP2.6. Since SSP cropland data do not distinguish between food/feed and energy crops, we took the difference in cropland between the baseline and mitigation scenarios in 2100 as a proxy value for energy crop area (assuming additional cropland expansion was driven by mitigation demand). Land-use change in 2100 was then compared to literature on land demand for agriculture, and land-conversion impacts on food production and biodiversity goals.

Ten semi-structured interviews with relevant experts were used to illuminate the process of knowledge legitimization in IAMs. These provided insights that could not be derived from technical documentation, into "how knowledge making [from IAMs] is incorporated into practices of… [climate] governance…, and… how practices of [climate] governance influence the making and use of [model-based] knowledge" (p. 3 [15]). The interviews informed our analysis of how land-use constraints are considered, and how different types of knowledge are included or excluded in IAMs.

We requested interviews from each of the modelling groups represented in Table 1. Policy experts were selected from those engaged in developing the land-use elements of countries' long-term low emissions strategies[iii]. Experts from four modelling groups and three countries agreed to be interviewed. Respondents are anonymously identified in the text as m(1, 2, 3, etc) for modellers and p(1, 2, 3, etc) for policy experts.

4. Mitigation-driven land-use change

In this section we present results on the type and scale of NETs found in IAM scenarios under evaluation. Below 2 °C scenarios in the SSP database rely on BECCS and afforestation for NETs, which is consistent with the larger database of scenarios used in AR5 [2]. We compare the scale of bioenergy demand and the associated land-use change in these mitigation scenarios to constraints related to food and biodiversity presented in the literature.

4.1. Bioenergy demand

The demand for primary bioenergy differs across scenarios and models. All mitigation scenarios show an increase in demand for bioenergy when carbon capture and storage (CCS) is introduced as a mitigation measure [30]. Three-quarters of bioenergy demand in <2 °C pathways under the SSPs is driven by BECCS (Fig. 1). Bioenergy supply in these scenarios is assumed from dedicated (second generation) energy crops – information on residue utilization is not provided [30]. Estimates for primary bioenergy supply in the literature span three orders of magnitude [31] and have engendered debate over the sustainability and

Table 1. Overview of SSP scenarios and land-use characteristics of SSPs (summarized from [30]). The land-use characteristics differ between SSPs and these underlying characteristics are treated differently across the IAM models. For this study, we analyzed five IAMs across the SSPs that achieved RCP2.6 (which excludes SSP3), for a total of 15 scenarios, as shown in row 2.
IAM, Integrated Assessment Model; SSP, Shared Socio-economic Pathway.

	SSP1 Sustainability	SSP2 Middle of the road	SSP3 Regional rivalry	SSP4 Inequality	SSP5 Fossil fuelled development
Land-use characteristics of SSPs	Strong regulation to avoid environmental trade-offs. High agricultural productivity, low food consumption. Land-use sector included in climate mitigation policies.	Medium regulation, deforestation rate declines slowly. Medium improvements in productivity, medium consumption levels, including meat. Partial land-sector inclusion in delayed global climate action.	Limited regulation, continued deforestation and low agricultural productivity development. Reduced global trade. Delayed climate action with minimal land-sector inclusion.	Low land-use regulation in poorer countries leads to high deforestation rates. High inequality in consumption levels. Immediate climate action – limited land-sector inclusion.	Medium regulation, slow decline in deforestation rates. High agricultural intensification. Increased consumption, high meat diets, high global trade. Delayed climate action – full land-sector inclusion.
RCP2.6 scenarios analyzed with IAM models	AIM GCAM4 IMAGE MESSAGE REMIND-MAGPIE	AIM GCAM4 IMAGE MESSAGE REMIND-MAGPIE	No scenario run from any model achieved RCP2.6 under SSP3 assumptions	AIM GCAM4	AIM GCAM4 REMIND-MAGPIE

carbon-neutrality of bioenergy use [32]. One difficulty in comparing estimates between sources is the inclusion of different bioenergy sources. More recent assessments have narrowed the range of what is considered technologically feasible for biomass production to 100–300 EJ/year by 2050, when utilizing all biomass sources, including residues [33,34].

When considering only dedicated cropland as a source for bioenergy, the IPCC indicates high agreement in the literature of a global technical bioenergy potential of below 50 EJ/year by 2050, with declining agreement for higher technical potentials (Fig. 11.20 [33]). When including all sources (crops, residues, etc) the IPCC indicates high agreement on a technical bioenergy potential of around 100 EJ/year by 2050, with low agreement for "possibly 300 EJ and higher" (p. 835 [33]). Based on net primary production, an upper biophysical limit for bioenergy from dedicated crops only (excluding residues) has been estimated at 190 EJ/year [31]. Yet achieving this scale of crop-based bioenergy production would require conversion of pasture, grasslands and natural land to energy crops on a scale that would have a significant impact on food production and biodiversity [31]. Constraining biomass harvest to protect food production and biodiversity suggests much lower limits to bioenergy from dedicated cropland (≈50–110 EJ/year in 2100) [35] although estimates are highly dependent on assumptions related to productivity, conversion efficiencies and food demand [35].

The total energy value of current global biomass harvest (food, feed, fibre and energy) is 230 EJ/year [31], of which current primary bioenergy production is ≈50 EJ/year [33]. Compared to current bioenergy production, the median value of bioenergy demand in the SSP database for RCP2.6 (black horizontal line in Fig. 1) suggests approximately a doubling in primary bioenergy demand by 2050, and more than a four-fold increase by 2100 (Fig. 1). Looking at specific scenarios, only six of the 15 analyzed are at levels with high agreement on technical potential (under 100 EJ/year) in 2050 (Supplementary Information). One mitigation scenario is under the constrained potential estimate of 100 EJ/year in 2100 (AIM SSP1) (Supplementary Information), although this estimate is for bioenergy from dedicated land-use only. As technical potential is presumably higher than socio-economic or sustainable supply potential, we suggest that the level of bioenergy

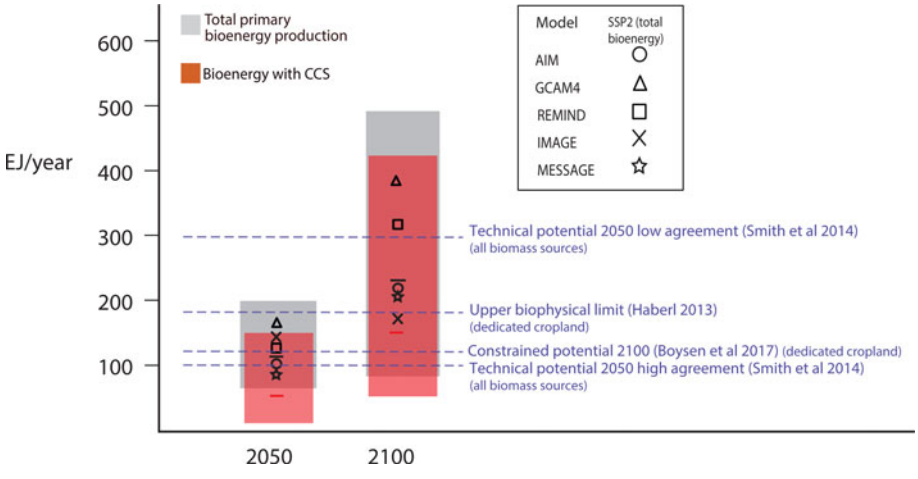

Fig 1. Bioenergy demand (total and with CCS) in 2050 and 2100 under RCP2.6.
Range is shown for all 15 SSP scenarios available for RCP2.6, as modelled by five IAMs (see Table 1); top of bar = maximum, bottom of bar = minimum, horizontal line represents median for total bioenergy (grey) and bioenergy with CCS (red). Model-specific values are shown with symbols for SSP2 (middle of the road development pathway) as an illustration. Dashed lines refer to potential primary bioenergy production assessments from the literature. Bioenergy demand in climate mitigation scenarios increase dramatically after 2050, with very few assessments of production potential after 2050. Data source: SSP Database (Note i), see supplementary Information.
CCS, carbon capture and storage; IAM, Integrated Assessment Model; RCP, Representative Concentration Pathway; SSP, Shared Socio-economic Pathway.

demand across all scenarios studied in 2100 is higher than what the scientific literature would suggest can be supplied without negative impacts on food production and biodiversity (Fig. 1).

This unsustainably high expectation for bioenergy production appears better explained by individual model assumptions than SSP narratives. When looking at expected bioenergy in 2100, demand varies more across models than across SSPs, with GCAM4 and REMIND-MAGPIE showing particularly high levels of bioenergy demand across all SSPs. Achieving these high levels of bioenergy production relies on optimistic assumptions for increased agricultural productivity, reduced food waste and shifts to less meat-intensive diets [30], all of which free land from agricultural production to be used for energy crops. In the next section we assess the scale of this assumed land conversion.

4.2. Land-use change

Popp *et al.* [30] report that all SSP scenarios for RCP2.6 show the same trend in land-use change: the area devoted to food and feed crops decreases, while land area devoted to energy crops increases; pastureland and other natural land decreases; and forest cover increases. While this trend is consistent across models and SSPs, our discussion here focuses on the scale (spatial extent) of land-use change as most relevant when considering the sustainability of modelled mitigation pathways.

Fig. 2 shows that both the range and extent of land-use change across all land types in the mitigation scenarios are large – in many scenarios some 500–1000 Mha pastureland and other natural land are converted by 2100 to allow expansion of forestland and total cropland (food/feed and energy crops combined) at similar scale. Energy crop area presented in Fig. 2 is based on our own calculations, as data are not available in the SSP database, and are the primary driver of cropland expansion in mitigation scenarios[iv]. Our 'proxy data' reading of energy crop area is confirmed by Popp *et al.* [30] who report an increase in energy crop area of between 270 Mha (SSP1) and 1517 Mha (SSP4) in RCP2.6. Hence the projection to increase global cropland (shown as cropped land in Fig. 2), up to nearly double that of today's extent of 1500 Mha [36], is predominantly for energy crops rather than crops to be used for food production.

Expansion in cropland area also comes at the expense of pastureland and 'other natural land', which show significant decreases of up to one billion ha (representing approximately 25% loss for each land category (from current extent of ≈3.4 billion ha of pasture land and ≈4 billion ha of other natural land)) [39], see also Note i. Land-use trade-offs are evident in mitigation scenarios. For example, natural land and forest protection result in loss of pasture land (MESSAGE), restricted cropland expansion results in higher loss of natural land (AIM) or forest protection driving loss of other natural land (IMAGE) (Supplementary Information). Assumptions around land-availability are also a key determinant of the cost of BECCS [37,38].

Estimates of demand for cropland in 2050 span a large range, compared with today's cropland extent of 1500 Mha [36]. Predictions for additional land needed by 2050 for food production range from as little as 70 Mha, assuming most future food demand is met through yield and efficiency increases rather than land expansion [39]; to 200 Mha by 2050 under more moderate productivity increase assumptions for agriculture [40]; to up to 1000 Mha under low productivity assumptions (involving a continuation of current trends) [40]. These projections highlight the challenge of meeting future agricultural food demand, excluding considerations of land for mitigation purposes, and the importance of productivity increases as well as demand-side measures in reducing agricultural land needs.

To assess end-of-century scenarios, the Planetary Boundaries concept, which defines a 'safe operating space for humanity' without compromising earth system function [41], can be used. The planetary boundary for land-use change was originally defined as cropland not covering more than 15% of ice-free land [41]. With current cropland covering 14% of ice-free land [42], further expansion of cropland risks crossing a safe land-use boundary. A broader land-systems change boundary was later defined as 75% of original global forest cover remaining. This is 13% higher than current levels [43], implying that at least 500 Mha of forests need to be restored in order to remain within the boundary. This area is estimated to be available for reforestation [44], and is broadly compatible with current political commitments, such as the Bonn Challenge[v]. In an analysis of impacts of BECCS on four planetary boundaries, Heck *et al.* (p. 2 [45]) find that "almost no biomass plantations can be

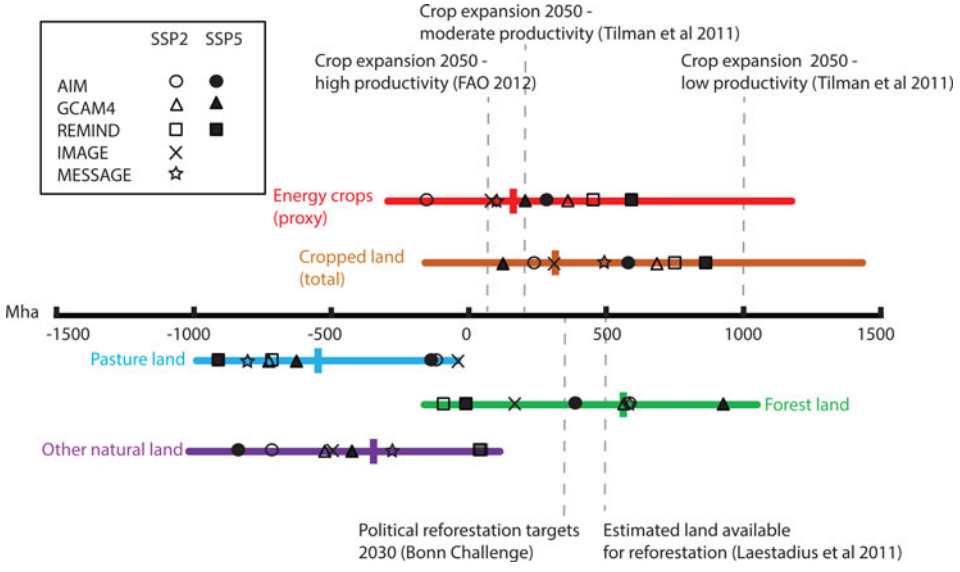

Fig. 2. Land-use change (Mha) in 2100 relative to 2010 under RCP2.6.
Horizontal lines represent the range across all available mitigation SSPs (1, 2, 4, 5) for each land-use type across five IAMs; vertical lines represent the median. Two SSPs are shown as examples: open symbols represent SSP2 (middle of the road), closed symbols represent SSP5 (fossil fuelled) development scenarios. Energy crops represented here are a subset of total cropland and inferred as the difference between cropland in the baseline scenario in 2100, and cropland in the mitigation scenario in 2100, taken to mean mitigation-driven cropland expansion. Data source: SSP Database (Note i). See Supplementary Information.
IAM, Integrated Assessment Model; SSP, Shared Socio-economic Pathway.

implemented" without increasing pressure on (already stressed) planetary boundaries related to biosphere integrity, land-system change, biogeochemical flows and freshwater use.

Taken together, this analysis shows that the scale of currently modelled 21st century land-use change for climate mitigation exceeds what may be considered sustainable with relation to food production needs and biodiversity protection, with no evidence to suggest supply could sustainably increase after 2050. Median outputs show primary bioenergy demand at more than double estimates constrained for food and biodiversity protection by 2100, with upper ranges almost five times higher, requiring a doubling of global cropland, and potential losses of up to a quarter of current pasture and other natural lands. The upper-range of forest cover increase, of one billion ha, is double the estimated land availability for reforestation (Fig. 2). IAM literature highlights the trade-offs inherent in land-based mitigation, reporting negative emissions as the main driver of land-use change across all SSP mitigation scenarios, with large-scale bioenergy production and afforestation reducing land for food/feed production and pasture [30]. We now examine how these trade-offs are translated into climate policy.

5. Co-production of integrated assessment mitigation pathways

The trade-offs apparent in modelled outputs indicate the need for a deeper understanding of whether and how such results gain political legitimacy. Using the analytical lens of co-production allows us to contrast the views of knowledge users (policymakers) and knowledge producers (modellers) to identify how land-based NETs have been legitimized as key mitigation options in IAM scenarios, assess the normative implications and propose ways forward. We identified four emergent themes from interviews relevant to concerns about land-based mitigation: uncertainty, feasibility, constraints and responsibility.

5.1. Uncertainty

The handling of uncertainty demonstrated the science-for-policy (regulatory science) nature of IAMs. The potential for land-based mitigation remains among the largest uncertainties in model outputs [30,46], and respondents referred to uncertainty regarding the extent of currently available land, projected future land-use demands and how these data limitations are dealt with in model assumptions. Many mitigation scenarios rely on pastureland, degraded land and grassland for energy crops, despite great uncertainties about the extent and availability of these lands [47]. When land availability is looked at in aggregate, overlapping and competing demands create a picture of land scarcity, and at the global scale land availability is often overestimated [42,48–50]. These empirical uncertainties make sustainable extents for land-use change difficult to determine.

Empirical uncertainty is often dealt with in models by drawing on expert judgment. As m1 reported during interviews: "in any modelling, there is an element of expert judgment". Yet relying on expert judgment means crucial underlying assumptions may remain unquestioned. M1 for example described determining technology availability as "what we can glean from published literature, uncertainty analysis and 'best guess'", but at the same time dismissed concerns of land scarcity, stating "we believe there is enough land for bioenergy". Another respondent (m4) described limiting bioenergy production to land not currently forested or used for agricultural crops, resulting in a greater extent of conversion of pasture land, grasslands and other natural lands – despite considerable uncertainty over how much land is available in these categories.

Policy experts (p1, p3, p4) recognized that while many of the model assumptions were largely 'unknowable', land availability arose as a key constraint on using bioenergy or forests for mitigation. As p3 put it: "the biggest question we kept running into is 'how much land is needed?'".

Interviews indicate that empirical uncertainty in IAM baseline assumptions is dealt with in a way that combines "elements of scientific evidence and reasoning with scientific and political judgment" (p. 229 [15]). This hybrid approach is typical of regulatory science, where results (and policy advice) are needed regardless of uncertainties. Yet in a context of uncertainty around global land availability, the use of technocratic expert judgment may risk overestimating the availability of potentially productive land for mitigation in modelled scenarios if it excludes consideration of social, cultural and political goals.

5.2. Feasibility

Model results determine technical and economic feasibility, which may not be consistent with 'real-world' constraints. The IAM community has been at pains to point out that IAM scenarios show multiple mitigation options that are not policy prescriptive, with assumptions and caveats carefully presented in publications. Riahi et al., for example, state techno-economic assumptions "need to be strictly differentiated from the feasibility of the transformation in the real world, which hinges on a number of other factors, such as political and social concerns that might render feasible model solutions unattainable" (p. 13 [29]). The feasibility of model results are only now being evaluated in terms of real world impacts [2,5,51].

Modeller respondents unanimously reflected the views of the IAM community, that model outputs do not 'imply' real-world feasibility. As one put it: "models are focused on the mitigation objective, and to some degree the feasibility depends on if we choose to do that level of mitigation. The models … can answer whether RCP2.6 is technologically possible, and say something about the cost, but we don't say it is feasible or not" (m2).

In response to questions on the reliance of modelled <2 °C pathways on BECCS, policy demand for deeper mitigation scenarios, as well as technological feasibility, proved key. Growing understanding of climate impacts consolidated policy around 2 °C. Improved understanding of the emission limits for these targets, along with international political commitments, drove policy demand for deep mitigation scenarios that achieve temperature targets of 2 °C and below [52,53]. Combining CCS with bioenergy to remove emissions from the atmosphere was first proposed in 2001 [54], and integrated assessment modellers subsequently found that it was 'logical' to include BECCS in 2 °C and below pathways, with "no real technological or ecological constraints to combining bioenergy and CCS" (m3). In fact, the availability of BECCS proved critical to the cost-efficiency, and indeed the theoretical possibility, of these deep mitigation scenarios [38,55], leading to systemic inclusion of BECCS in RCP2.6 scenarios included in AR5. For the more recent SSP scenarios, assumed technology costs continue to be highlighted. As m1 said: "what happens in those models is going to be completely dependent on your assumptions about the costs associated with different technologies". BECCS was justified as "assumed availability based on the SSP storyline and existence of bioenergy supply" (m2).

BECCS was therefore introduced to models because it was considered technically feasible and cost-effective. Policy experts (p2, p3, p4), while agreeing that modelled outputs were not intended to be policy prescriptive, expressed concern over the feasibility of the scale of bioenergy and land-use change assumed. Hence technological, rather than real-world feasibility, led to including large-scale BECCS in models. Critiques of NETs reliant pathways assert this scale of land-based mitigation poses unacceptable trade-offs [4,10].

5.3. Constraints

'Constraints' refers to the inclusion of assumptions in the baseline to limit model options for ways to meet the desired target. Relatively few constraints to land-based mitigation were identified beyond the SSP storylines, based on interviews and SSP model documentation[vi]. Policy constraints were described by m1, m2 and m4 as being translated into IAMs through price (consumer demand) and subsidies (policy demand). Certain models had specific constraints, such as the protection of cropland for food production in IMAGE (inclusion of food demand in the baseline and no bioenergy production on agricultural or forested land). Other models allow food production to compete for land based on cost. Reducing forest loss (through protected area constraints or limiting the rate of deforestation) is used as a proxy for biodiversity protection in many models, while other natural lands are subject to competing demands.

When trying to balance competing land-use demands, p3 commented that "the real victim in all of this is grasslands… the only way we can achieve [bioenergy expansion] is by encroaching on, ideally, low productivity pasture lands" (p3). Similar dynamics can be seen in global-scale IAM scenarios, where both pastureland and 'other natural land' decline in all mitigation scenarios, often substantially (Fig. 2). This raises questions of who may be impacted by the assumed availability of 'low productivity' or degraded land, which often has high biodiversity and existing social and cultural value [47,56]. Gibbs and Salmon note, "even a precise map of the physical area of degraded land would significantly overestimate its potential by neglecting its myriad social, environmental, and political constraints" (p. 19 [47]).

Some modellers reported that normative constraints were minimized or excluded due to concerns that including value-based assumptions undermines the objectivity of model outputs. For example, m3 expressed the view that including constraints in baseline assumptions would add an unacceptable layer of political or 'value-based' judgment, making model results in-transparent and unacceptable to peer review. This reflects an epistemic commitment where "peer review plays a significant role in establishing the credibility of expert knowledge" (p. 233 [15]). Acknowledging the lack of baseline constraints, m4 felt additional policy measures were needed for food security and biodiversity protection.

By contrast, policy experts felt models should include explicit constraints for more realistic outcomes. P4 expressed concern over the lack of model structures to accommodate "concerns that cannot be monetized or quantified". P3 highlighted the importance of the 'practitioner perspective', noting how infrequently modellers "had encountered sector specific practitioners… who have a granular understanding of cost points, opportunity costs for landowners, cultural considerations, etc." When using IAMs for national modelling, policy experts and modellers had to find new ways of dealing with model assumptions to achieve more realistic results. Describing the need to 'force' a different price on the land sector to prevent unrealistically high afforestation levels, p3 noted that modellers found it 'unscientific' to introduce constraints to achieve a desired output: "from a modelling perspective they thought – 'this is not scientific, this is not how we do things'". The reluctance to include societal objectives as baseline constraints can be seen as a form of boundary work, defining IAMs as objective science that confers results with "unshakeable authority" (p. 236 [15]).

5.4. Responsibility

While IAM scenarios suggest that a below 2 °C pathway relying heavily on land-based NETs is theoretically possible, closer examination of the assumed scale of land-use change indicates that choosing this path could exacerbate significant problems of land scarcity, food insecurity and biodiversity loss. Can these caveats and trade-offs be effectively communicated in the 'up-take' of results into climate policy? Whose responsibility is it to do so?

All modellers interviewed viewed the identification and communication of such complexities, links and impacts as responsibilities for the modelling community. However, as m3 observed, while "we do our best" to communicate the complexities and trade-offs inherent in model assumptions, this is often 'lost in translation' between the modelling and policy worlds. Others (m1, m2) described how the complexities of SSP scenarios themselves raise problems, pointing to non-evident results and the number of interacting variables as barriers to clear communication and understanding of model outputs.

While the modelling community is careful to communicate potential impacts and consequences of modelled options, published literature [57] and interview responses (m1, m2, m3, m5) strongly defend the position that models provide objective input to the climate policy debate. For example, m3 suggested that "running [a model] on current political feasibility is not transparent. It involves making many assumptions". Yet the context and assumptions communicated in the scientific literature are often lost when used in political contexts, as acknowledged by p1: "I see modellers saying 'you have to interpret this in the context of all these assumptions…' but for the most part, policymakers are not good users of modelled outputs".

How model results are communicated and to what degree trade-offs are recognized and accepted is of critical importance, given that negative emission scenarios dominate the international climate policy landscape, a point that can be illustrated in the uptake of NETs add hyphen (NETs-reliant) reliant scenarios into the 2015 Paris Agreement.

Crucial details and qualifications present in longer publications are often omitted from pithier policy statements. For instance, the IPCC AR5 Summary for Policymakers clearly states that below 2 °C scenarios are reliant on NETs: "characterized by lower global GHG emissions in 2050 than in 2010, 40 to 70% lower globally, and emissions levels near zero $GtCO_2eq$ *or below* in 2100" (p. 10, emphasis added [58]). Uncertainties were highlighted in the next paragraph: "There is uncertainty about the potential for large-scale deployment of BECCS, large-scale afforestation, and other CDR technologies and methods" (p. 11 [58]). By contrast, during the lead-up to the Paris climate summit, a critical G7 statement merely included an unqualified commitment to "40 to 70% [GHG emissions] reductions by 2050 compared to 2010" (p. 12 [59]). This helped pave the way for these same (NETs reliant) pathways to be included in the decision adopting the Paris Agreement[vii] without acknowledging the reliance of

less ambitious 2030 emission reduction targets on future availability of NETs.

Whether the absence of reference to NETs in the Paris Agreement reflects a lack of understanding among high level policymakers or their deliberate avoidance of this politically contentious issue is impossible to know, but the adoption of these targets signals an acceptance of large-scale NETs, without any critical policy or public debate over potential impacts and lock-in effects, or discussion of more ambitious mitigation pathways that would reduce the need for NETs. Greater transparency around the normative choices being made in modelled mitigation pathways would contribute to a more open debate.

6. Conclusions

After comparing model results for deep mitigation pathways with the literature on bioenergy supply and land availability, we suggest that the level of land-based mitigation in current IAMs is likely to negatively impact food production and biodiversity, due to extensive land-use change. The introduction of BECCS into modelled scenarios is constrained by modellers using techno-economic feasibility, rather than real-world feasibility, with boundaries carefully enacted to maintain authority of model results and legitimize the inclusion of BECCS and other land-based NETs in future mitigation pathways. While the potential for risks to food production and biodiversity are communicated by modellers, this is often lost in the political uptake of model results.

Integrated assessment modelling is simultaneously scientific and political, and can be seen to have had substantial policy impacts leading up to the Paris Agreement. It continues to have significant influence in international and national climate policies. While IAM scenarios generate valuable knowledge for climate policy, paradoxically, the intention for modelled scenarios to be non-determinative is undermined if NETs-reliant pathways are used to justify higher near-term emissions, assuming these can be removed at a later date to achieve a <2 °C pathway. This 'lock-in' potential of mitigation pathways reliant on large-scale carbon removal requires more critical examination by decision-makers and other stakeholders. Highlighting the shift from predictive to determinative use of models that has occurred (with IAM outputs treated as regulatory science) could open the way for more serviceable knowledge production.

A process in which modelling teams and policy experts systematically negotiate model assumptions that better account for real world constraints could produce what one policy expert (p3) described as 'purposeful modelling'. Purposeful modelling embodies a reflexive approach to the co-production of scientific knowledge. Closer negotiation between knowledge producers and knowledge users could lead to a more informative set of mitigation scenarios by explicitly including social and environmental goals in models, and contrasting the use of these 'constrained' and 'unconstrained' scenarios in the scientific and policy-oriented literature. This would come closer to Jasanoff's 'serviceable truth' by opening key assumptions for consideration, rather than embedding contestable normative assumptions within scientific authority. While this may come at the expense of the perceived scientific objectivity of modelled scenarios, it would allow for a more critical interrogation of the value-based and ethical choices inherent in any scenario-building exercise.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/sus.2018.6

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Ethical standards. The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

Notes

i SSP Database, 2012–2016. Available at: https://tntcat.iiasa.ac.at/SspDb.
ii SSP scenarios compatible with a 1.5°C pathway were not available in the SSP database at the time this paper was published.
iii Long-term strategies, as requested under Article 4.19 of the Paris Agreement, are listed at: http://unfccc.int/focus/long-term_strategies/items/9971.php. By the end of 2016, the US, Canada, Mexico and Germany had submitted strategies.
iv Except for AIM, where cropland area decreases in all mitigation scenarios except SSP5, but at the expense of large decrease in other natural land.
v See http://www.bonnchallenge.org.
vi Available at: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about
vii UNFCCC/CP/2015/L.9/Rev.1 Paragraph 17 refers to the need for below 2°C pathways to reduce emissions to 40 $GtCO_2$ by 2030, a pathway consistent with 500–950 $GtCO_2$ cumulative removals this century.

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5.2 Land-use change in 1.5 °C pathways

Here I evaluate the scale and type of negative emissions in IAMs, and associated land-use change, for the most recent generation of 1.5 °C compatible scenarios under the SSP framework. I compare the scale of land-use change in modelled pathways with estimates from across the literature on the sustainable potential for terrestrial carbon dioxide removals, analyzing bioenergy supply and other land-based removals. I then briefly assess the handful of 1.5 °C scenarios with no or limited BECCS, to determine what are the different mitigation options that allowed for the minimization of negative emissions, and what are the resultant outcomes in relation to sustainable development objectives.

Methods

Using the latest generation of deep mitigation scenarios for limiting warming to below 1.5 °C, harmonized under the SSPs (Rogelj et al. 2018), I here analyze the land-use outcomes from five IAMs. These scenarios are known as SSP*x*-1.9, as they represent concentration pathways of 1.9 W/m (Rogelj et al. 2018), compatible with a warming limit of 1.5 °C. Of the five SSPs, no scenario managed to achieve a forcing level at or below 1.9 W/m under development assumptions for SSP3. Across the remaining SSPs, 1.9 W/m scenarios were achieved from six models presented in Rogelj et al. (2018): AIM, IMAGE, REMIND-MAGPIE, GCAM4, MESSAGE, WITCH. Of these six, WITCH was excluded from this analysis due to incomplete data-sets related to land-use variables. Table 5.2 outlines the IAM scenarios for SSP*x*-1.9 analyzed here, as well as the RCP2.6 pathways analyzed in Section 5.1, above.

	SSP1 Sustainability	SSP2 Middle-of-the road	SSP3 Inequality	SSP4 Reginal rivalry	SSP5 Fossil-fueled dev
15 RCP2.6 scenarios *(Riahi et al 2017)*	AIM GCAM4 IMAGE MESSAGE REMIND-MAGPIE WITCH-GLOBIOM	AIM GCAM4 IMAGE MESSAGE REMIND-MAGPIE WITCH-GLOBIOM	No scenario run from any model achieved RCP2.6 or 1.9 under SSP3 assumptions	AIM GCAM4 WITCH-GLOBIOM	AIM GCAM4 REMIND-MAGPIE WITCH-GLOBIOM
11 RCP1.9 scenarios *(Rogelj et al 2018)*	AIM GCAM4 IMAGE MESSAGE REMIND-MAGPIE	AIM GCAM4 MESSAGE REMIND-MAGPIE		WITCH-GLOBIOM	GCAM4 REMIND-MAGPIE

*nb: WITCH-GLOBIOM was excluded from analysis due to incomplete data-sets on land-use

Table 5.2: Scenario runs under SSP assumptions for RCP2.6 and RCP1.9

I assessed the scale of primary bio-energy demand and the extent of land-use change in SSP*x*-1.9 by examining the model outputs for these two variables from the eleven scenarios analyzed (Table 5.2, row 2). The analysis carried out then parallels the methodology described in Section 5.2: I performed a simple comparison of model results for primary bioenergy demand in 2050 and 2100 to a review of the literature assessing sustainable bioenergy supply potentials. For land-use change I compared model results to literature estimating the impacts of land-use change on food security and biodiversity.

I analyzed land-use change according to the categories in the SSP database, which are also consistent with those presented by Rogelj et al. (2018): cropland (divided into cereal crops and energy crops), pastureland, and forestland (undifferentiated between plantation and natural forest). Data for the category 'other natural land' (non-agricultural and non-forested ice- and desert-free land), presented in the SSP database for RCP2.6 scenarios is not provided for SSP*x*-1.9, meaning it is not possible to compare the difference in land-use change in this category between 2 °C and 1.5 °C pathways, nor to assess the extent of land-use change in natural lands in SSP*x*-1.9. While the extent of land-use change in mitigation scenarios relative to a 2010 baseline scenario was not provided in the SSP database for RCP2.6, this information is presented in the supplementary

information for SSP*x*-1.9 (Rogelj et al. 2018). Hence, for this section I draw directly on these data to compare land-use change in 2100 against a review of the literature on land demand for agriculture, and land-conversion impacts on food production and biodiversity goals. For comparison, I also look at the extent of bioenergy demand and land-use change in a small number of studies that purposely set out to exclude or minimize carbon dioxide removal options.

After assessing and comparing the level of primary bioenergy demand and extent of land-use change in RCP2.6 (section 5.1), SSP*x*-1.9 scenarios and the alternative 1.5 °C scenarios, I discuss the implications for sustainable development objectives from the policy options provided as scientific input to the global climate governance.

Results

This section assesses the extent of bioenergy use and land-use change in 1.5 °C compatible pathways under the SSP framework (SSP*x*-1.9). It is important to note that the modelled pathways depicted in Rogelj et al. (2018) show that no 1.5 °C scenario peaks after 2020, and for scenarios with higher emissions in 2030, net-zero emissions must be achieved earlier in order to limit warming to 1.5 °C (requiring greater volumes of CDR). Hence, modelled scenarios for 1.5 °C highlight the importance of near-term mitigation in minimizing reliance on negative emissions.

Primary bioenergy demand in these scenarios in 2050 varies from 50 to 310 EJ /yr (see Figure 5.3). By 2100, demand is projected to increase to up to 450 EJ /yr, with a median of 260 EJ /yr (Figure 5.3). Biomass supply is reported to be derived from both energy crops and residues (see Rogelj et al. 2018, supplementary figure 13c, and figure 1). As with RCP2.6 scenarios, bioenergy use is driven largely by demand for BECCS, with a range spanning from150-700 Gt CO_2 (SSP1) to 950-1200 Gt CO_2 (SSP5) in cumulative removals required over the century (Rogelj et al. 2018). The requirement for BECCs more than doubles when going from SSP1 (sustainability) to SSP5 (fossil-fueled development) pathways, showing the importance of future development pathways in minimizing reliance on NETs (Rogelj et al. 2018). However, the median demand for bioenergy

across all SSPs also doubles from 2050 to 2100 (Figure 5.3) , showing the expected availability of scaled up biomass supply in the second half of the century.

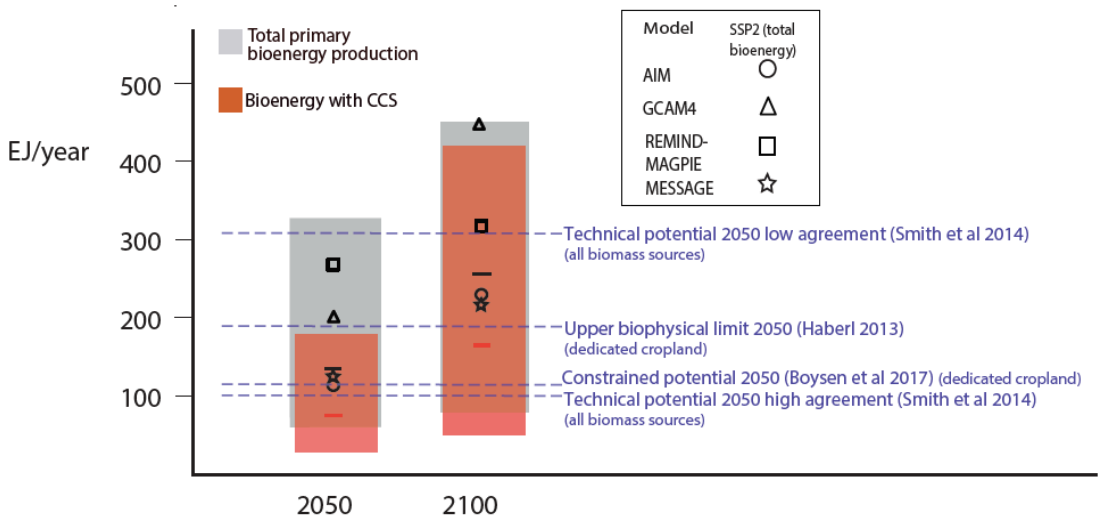

Figure 5.3: Primary bioenergy demand (modern and with CCS) in 2050 and 2100 for SSPIx-1.9
Range is shown for all 11 scenarios available for SSPx-1.9; top of bar = maximum, bottom of bar = minimum, horizontal line represents median for total bioenergy (grey) and bioenergy with CCS (red). Model-specific values are shown for SSP2 (middle of the road development pathway) as an illustration. Dashed lines refer to primary bioenergy production assessments from the literature. Bioenergy demand in climate mitigation scenarios increase dramatically after 2050. Data from Rogelj et al. 2018.

Similar to the results for RCP2.6 presented in the preceding section, land-use change sees area for cereal crops decrease while energy crops expand to an area equivalent to today's global cultivated land area, while pasture land decreases at a similar magnitude (Figure 5.4). In 2100, energy crop area increases by 200-1100 Mha, with SSP1 showing a lower range than SSP2. Cereal crops decrease by 270 Mha in SSP2, and 320 Mha in SSP1, with the exception of AIM SSP2-1.9, which shows an increase of 50 Mha. Pasture land decreases by between 50 and 1200 Mha across all SSPs, with inter-model variation rather than SSP narratives explaining much of the difference. Forestland expands in all scenarios but one (REMIND SSP2-1.9), with increases of 50 to 1550 Mha, again with inter-model variation explaining more of the differences than SSP narratives. Data for other natural land is not available for the SSP*x*-1.9, so the impacts of the expansion of other land-uses on natural land cannot be assessed.

When looking at SSP*x*-1.9 scenarios compared to RCP2.6, primary bioenergy contribution is double that of RCP2.6 by 2050, butt by 2100 is within the same range, showing the earlier deployment of NETs in 1.5 °C scenarios. Median outputs show primary bioenergy demand at more than double estimates constrained for food and biodiversity protection by 2100, with upper ranges almost five times higher, requiring global cropland area to almost double, and potential losses of more than a quarter of current pasture land. While bioenergy demand is similar across RCP2.6 under the SSPs and SSP*x*-1.9, land-use change is more extensive in the 1.5 °C compatible scenarios, with cropland and forests showing greater increase, pastureland showing greater decrease, and other natural land not reported for SSP*x*-1.9 (Figure 5.4).

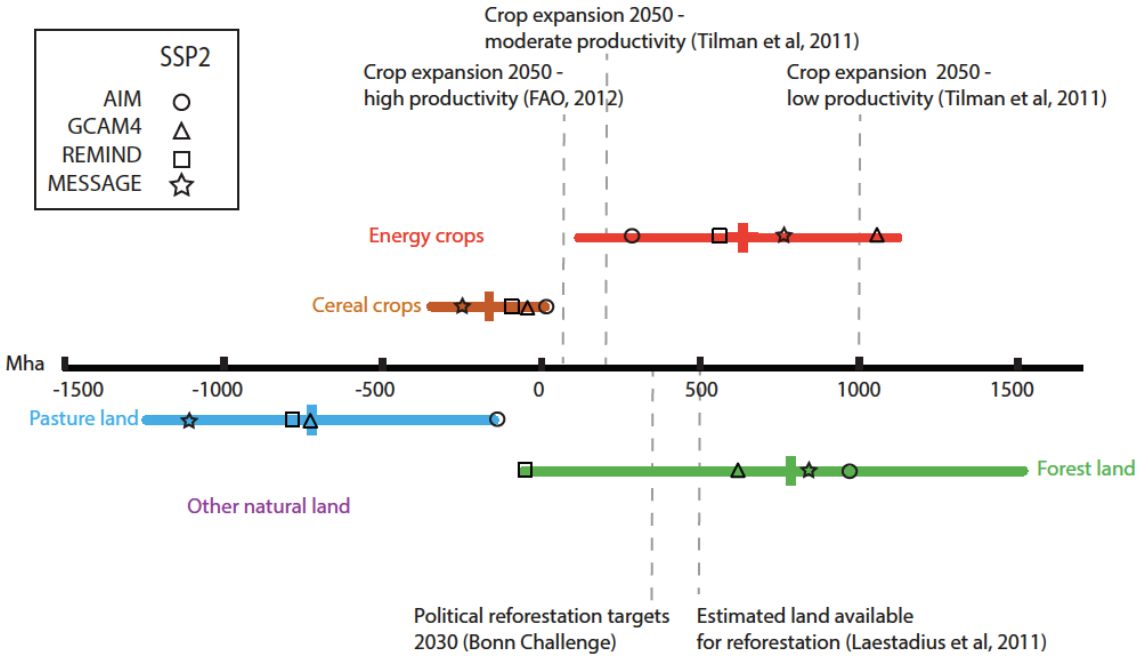

Figure 5.4: Land-use change in 2100 relative to 2010 under SSPx-2.6
Land-use change (Mha) from 2010 to 2100 under SSPx-1.9. Horizontal lines represent the range across all available mitigation SSPs (1, 2, 5) for each land-use type across five IAMs; vertical lines represent the median. Two SSPs are shown as examples: open symbols represent the SSP2 (middle of the road) development scenario, closed symbols represent SSP5 (fossil-fueled development). Data from Rogelj et al. 2018.

'Alternative' 1.5 °C scenarios

In this section I discuss a small number of IAM scenarios that have purposely limited or excluded negative emissions from future mitigation pathways (Holz et al. 2018; van Vuuren et al. 2018; Grübler et al. 2018). All of these studies emphasize early and steep reductions in fossil fuel use, with widespread electrification and renewable energy deployment.

Notable differences from more 'conventional' deep mitigation scenarios analyzed above included ambitious assumptions of non-CO_2 emission reductions (requiring agricultural intensification); behavioral change with reduced rates of consumption, travel and meat intake globally; and stronger demand side mitigation in transport and building sectors. The striking finding from van Vuuren et al. (2018) is that while these various mitigation options can reduce reliance on BECCs in 1.5 °C scenarios, all of the alternative mitigation options must be successfully undertaken to completely exclude the use of BECCS, with still some reliance on afforestation for carbon dioxide removal.

Grübler et al. (2018) investigate a low energy demand scenario, where global primary energy demand in 2100 is 40% lower than today, which is well below comparable IAM scenarios in the IPCC's Fifth Assessment report, and the more recent scenarios under the SSP framework. The authors achieve this energy reduction pathway through rapid behavior driven change in how energy is consumed, with a scaled down global energy system that is strongly focused on efficiencies in energy end use (Grübler et al. 2018). CCS is explicitly excluded from this scenario (for fossil or bioenergy), and the lack of reliance on negative emissions allows for significant sustainable development co-benefits. An important side-effect of low energy demand is that there is less demand for biofuels even in the absence of CCS, which in many other scenarios remains high (Grübler et al. 2018). Cropland areas in the Grübler et al. (2018) scenario remain relatively constant, with small increase in forest areas and natural land, avoiding the land-use trade-offs and negative impacts on food security and biodiversity that large areas of land-use change implies.

Holz et al. (2018) highlight the difference between net and gross emission reduction rates, finding that when reliance on carbon-dioxide removal is constrained, emission reduction rates increase to levels without historical precedence. The authors note that this points to a general trade-off between the scale of carbon-dioxide removal and the required stringency of GHG reductions, with efforts to limit reliance on negative emissions meaning societies "will have to investigate rates of CO_2 reductions well outside of what is currently deemed plausible" (Holz et al. 2018, p.10).

In all of these scenarios, land-use change was minimized, with diverse benefits for biodiversity, health, poverty alleviation, and climate reported (Grübler et al. 2018). However, these pathways rely on ambitious assumptions of non-CO_2 emission reductions, behavioral change, and changes in how energy is delivered and used. Without such ambitious (non-technological and un-costed) assumptions, the scale of modeled 21st century land-use change for bioenergy-driven climate mitigation exceeds what may be considered sustainable with relation to food production needs and biodiversity protection. IAM publications presenting low emissions scenarios reliant on negative emissions are careful to highlight these risks. Popp et al. (2017) highlight the trade-offs inherent in land-based mitigation, with reduced land for agricultural use, while Rogelj et al. note that "bioenergy is used in large amounts in all 1.9Wm−2 scenarios, and this can raise concerns for food security or biodiversity" (2018, p.3), and that "integrated policy packages are required that ensure food security is achieved along with climate mitigation" (2018, p.4). Yet these warnings are generally lost in the uptake of modeled outcomes into the policy discourse.

Conclusions

Since I began conducting this research, other studies have analyzed similar questions, concluding that great uncertainties, both technical and institutional, remain relating to BECCS being deployed at scale, with key requirements for the sustainable deployment of BECCS including strong governance with integrated policies for energy, land use and water management; ensuring bioenergy and food do not compete for land, and realizing that future bioenergy supply is a key

uncertainty (Fajardy & Mac Dowell 2017; Vaughan & Gough 2016; Muratori et al. 2016; Gough & Vaughan 2015; Kline et al. 2016; Popp 2011). Creutzig et al. (2014) perhaps best sum up the underlying problem with projecting (and relying on) large volumes of bioenergy for future climate mitigation: “How much biomass for energy is technically available in the future depends on the evolution of a multitude of social, political and economic factors, e.g., land tenure and regulation, diets, trade and technology” (Cruetzig et al. 2014, p.918). Vaughan et al., note that the purpose of IAMs is to explore possible futures and uncertainties associated with those futures (not intended to provide predictions of the future), highlighting the problem of IAMs creating a lock-in effect when NETs are relied on, turning a predictive tool into a determinative one that risks becoming the "default mitigation strategy" (Vaughan et al. 2018, p.2). In light of this insight, it is of critical importance that IAMs (and other scenario building efforts for very low emissions futures) consider a range of options. Prioritizing mitigation options that bring significant co-benefits will be essential for effective policies to reduce GHG emissions at scale.

Given that the remaining cumulative carbon budget (2016-2100) for 1.5 °C is reported as being between -175 to 475 Gt CO_2 (Rogelj et al. 2018), there is no doubt that gigatonne-scale atmospheric carbon-dioxide removal will be required to limit warming to 1.5 °C. The key questions for society now revolve around to what extent can reliance on carbon-dioxide removal be minimized (through more aggressive mitigation to avoid fossil fuel emissions), and what alternatives for carbon-dioxide removal exist to avoid the negative social and environmental impacts associated with BECCs and afforestation, already highlighted in the literature.

This section has found the scale of land-use change in 1.5 °C scenarios under the SSP framework to be similar to 2 °C scenarios, with all of the attendant impacts on food security and biodiversity. The ‘alternative’ pathways with no or limited negative emissions assume potentially unrealistic scale of behavior change (ie: most of the remaining mitigation potential that is not found in the SSP scenarios is in assuming global reductions in consumption such as switch to reduced meat diets and

reduced travel, etc), although Grübler et al., (2018) found that achieving a significant reduction in energy demand, rather than the growth assumed in most IAMs, alleviated the requirement for NETs.

A second important finding is that the way information is presented in the new publications (i.e. 2018 on) greatly increases the transparency – more data is available, including gross rather than net carbon-dioxide removal, and explicit figures on scale of land-use change are published. In addition, the way results are presented has changed, with caveats and risks, that were always highlighted, made much more explicit, and a thorough discussion of what 'technical feasibility' in models means (c.f. Rogelj et al. 2018).

While some level of negative emissions will be required for 1.5 °C pathways, the scale and means to achieve carbon dioxide removals vary greatly, with vastly different socio-economic consequences and co-benefits. These factors must all be considered by policy-makers in determining near-term mitigation pathways, rather than relying only on options presented via cost-optimization modelling. A process of 'purposeful modelling', as described in the conclusions to Section 5.1, where closer negotiation between knowledge users and knowledge producers could lead to results that illuminate, rather than obscure, the range of choices facing society for future mitigation pathways the achieve the objectives of the Paris Agreement.

Chapter 6

Future mitigation pathways aligned with SDGs

In Chapter 5, I analyzed the scale of reliance on negative emissions in modelled scenarios of 2 °C and 1.5 °C and the subsequent impacts on land-use and associated trade-offs with sustainable development objectives. A key finding of Chapter 5 is not just that open debate is needed, but that it is the role of science (in society) to provide a range of choices for decision makers to weigh alternatives.

Chapter 6 aims to contribute to such a debate by applying explicitly normative criteria related to sustainable development objectives to the attainment of land-based negative emissions. This aligns with the methodological framework to distinguish between normatively 'good' and 'bad' co-production based on to what degree the scientific process of knowledge production accounted for socially sanctioned questions and objectives. In this case, I take these objectives to be the 2015 Sustainable Development Goals (SDGs), a globally agreed set of values and goals for sustainable development. In this chapter, I propose an evaluation framework to assess potential land-based mitigation options, based on the trade-offs and synergies with three SDGs particularly reliant on land: SDG 2 (zero hunger); SDG 13 (climate action); and SDG 15 (land-use).

This Chapter, which represents the last of the three research chapters, consists of a paper published in *International Environmental Agreements* in 2017, which is included here in full. This paper develops a framework for understanding the risks and potential consequences of relying on negative emissions, and then uses this to assess negative emissions options against impacts on the three SDGs outlined above. The paper concludes with an indicative assessment of the potential for negative emissions that might be more aligned with broader sustainability goals. An interesting conclusion to note, and to discuss further in the next chapter, the final concluding chapter, is that a different set of organizing, or decision-making assumptions, as is the case here compared to the

IAM assessment, results in very different outcomes and implications for global climate governance in relation to land.

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ORIGINAL PAPER

6.1 Land-based negative emissions: risks for climate mitigation and impacts on sustainable development

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Abstract This paper focuses on the risks associated with "negative emissions" technologies (NETs) for drawing carbon dioxide from the atmosphere through photosynthesis and storing it in land-based sinks or underground. Modelled mitigation pathways for 1.5 °C assume NETs that range as high as 1000 Gt CO_2. We argue that this is two to three times greater than the amount of land-based NETs that can be realistically assumed, given critical social objectives and ecological constraints. Embarking on a pathway that assumes unrealistically large amounts of future NETs could lead society to set near-term targets that are too lenient and thus greatly overshoot the carbon budget, without a way to undo the damage. Pathways consistent with 1.5 °C that rely on smaller amounts of NETs, however, could prove viable. This paper presents a framework for assessing the risks associated with negative emissions in the context of equity and sustainable development. To do this, we identify three types of risks in counting on NETs: (1) that NETs will not ultimately prove feasible; (2) that their large-scale deployment involves unacceptable ecological and social impacts; and (3) that NETs prove less effective than hoped, due to irreversible climate impacts, or reversal of stored carbon. We highlight the technical issues that need to be resolved and—more importantly—the value judgements that need to be made, to identify the realistic potential for land-based NETs consistent with social and environmental goals. Given the critical normative issues at stake, these are decisions that should be made within an open, transparent, democratic process. As input, we offer here an indicative assessment of the realistic potential for land-based NETs, based on a precautionary assessment of the risks to their future effectiveness and a provisional assessment of the extent to which they are in conflict with sustainable development goals related to land, food and climate.

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Keywords Negative emissions technologies (NETs) · Ecosystem restoration · SDGs · Equity · Sustainable development

Abbreviations

BECCS	Bioenergy with carbon capture and storage
GHG	Greenhouse gasses
HANPP	Human appropriation of net primary production
HWP	Harvested wood products
IAM	Integrated assessment modelling
NETs	Negative emissions technologies
NPP	Net primary production
SDGs	Sustainable development goals

1 Introduction

The Paris Agreement on climate change (UNFCCC 2015) has thrown the spotlight on very low emissions scenarios, with its call to hold global average temperature increase to "well below" 2 °C, and to "pursue efforts" to limit temperature increase to 1.5 °C. Such an ambitious objective raises questions about the extent to which removing emissions from the atmosphere may be necessary to achieve this, and the equity implications of doing so. One result of the focus on low emissions scenarios is that "negative emissions technologies" (NETs), referring to the removal of carbon dioxide from the atmosphere, have increasingly appeared—explicitly or implicitly—in analyses and discussions of options for addressing climate change.

There is a wide range of proposed negative emissions options (Williamson 2016). In this paper, we focus on those most commonly included in modelled scenarios for 2 °C and lower pathways, to assess the risks posed by such mitigation options. Proposals for NETs are currently dominated by land-based options, which are increasingly seen as cost-effective and feasible components of climate mitigation strategies. The two options being widely considered are large-scale reforestation and bioenergy in combination with carbon capture and storage (BECCS).[1] Less commonly assessed is the potential for landscape restoration—both restoration of closed canopy forests and "mosaic" restoration of more intensively used landscapes—to contribute to climate mitigation.

The Paris Agreement states that efforts to achieve the long-term temperature goal must be carried out "on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty" (UNFCCC 2015). This outlines an obligation for climate mitigation action to be in line with the sustainable development agenda, including the right to development. Gupta and Arts (2017) have elaborated on the links between Agenda 2030 and the principle of equity within the Paris Agreement as requiring a "just" approach to climate action—necessitating reduced inequality between states, and international cooperation for sustainable development. Yet, proposals for large-scale reliance on land-based mitigation for negative emissions pose clear and significant risks to sustainable development. At the same time, there is unexplored potential for synergies between climate

[1] Note that soil carbon sequestration is excluded from modelled pathways due to scientific uncertainties, and so we do not include it here as a common NET option.

mitigation in the land sector and the achievement of sustainable development goals (SDGs[2]).

We argue that extending the near-term carbon budget by presupposing the future availability of NETs poses risks that are of a different nature than those posed by conventional mitigation options. Accepting these risks may lock us into much higher levels of future warming than intended, and/or force us to confront considerably higher social and ecological costs. Indeed, taking on such risks may substantially undermine society's overall mitigation efforts.

As part of this special issue on *Achieving 1.5 °C and Climate Justice*, the aim of this paper[3] is to highlight those risks, and to identify—and very roughly quantify—sustainable NETS potential in terms of both the magnitude and the type of land-based mitigation options that could contribute. Section 2 introduces three categories of risks to the future effectiveness of NETs and develops a framework to evaluate these risks in the context of land-based NETs. Section 3 evaluates land-based NETs by identifying mitigation estimates found in the literature and reviews potential impacts on key SDGs reliant on land. It then tentatively suggests an estimated potential for those negative emissions options that pose less risk of conflicts with sustainable development objectives. Section 4 discusses the implications of these findings for the objective of limiting warming to below 1.5 °C in the light of the Paris outcome on a global mitigation goal. Section 5 concludes.

2 Risks to achieving land-based negative emissions

This section identifies three sequential levels of risks posed to the future effectiveness of NETs generally and uses these to examine land-based NETs specifically.

2.1 Risk evaluation framework

All mitigation options come with risks that they might be less effective than expected. As global society seeks to reduce emissions, it will need to assess the effectiveness of its mitigation efforts and their adverse impacts, and continually adapt strategies accordingly.

Negative emissions techniques pose a very different class of risks, however—one from which there may be no way to recover if things go wrong. This is because they are typically discussed as options to be deployed later in the century, to "undo" emissions that occurred earlier. This, the logic goes, would enable us to stay within a given carbon budget in the long run, even after having greatly exceeded it in prior decades.

In the idealized world of techno-economic models, with perfect foresight and confident projections of costs and potentials, this strategy appears eminently sensible. It buys time, allowing societies to avoid near-term mitigation costs by relying on options that are deferred to the comfortably distant future. It takes the pressure off sectors where mitigation is difficult, such as aviation. Tavoni and Socolow (2013), noting that negative emissions have increasingly been incorporated into modelled assessments of mitigation pathways, point out the ironic trend in recent years: "Thus, paradoxically, despite little progress in international climate policy and increasing emissions, long-term climate stabilization

[2] The United Nations SDGs are explained here: http://www.un.org/sustainabledevelopment/sustainable-development-goals/.

[3] This paper is based on research originally presented in a working paper, available here: https://www.sei-international.org/mediamanager/documents/Publications/Climate/SEI-WP-2016-08-Negative-emissions.pdf.

through the lens of IAM [integrated assessment modelling] appears easier and less expensive," a concern echoed in the recent literature (Anderson and Peters 2016; Williamson 2016).

In the real world, this "easier and less expensive" strategy poses fundamental risks to the realization of low emissions pathways, due to uncertainties about whether society will ultimately be able to realize the benefits of NETs when they are needed, as well as fundamental risks to development objectives, due to potentially unacceptable social and ecological impacts of negative emissions. We highlight three sequential risks, shown in Fig. 1.

First, the measures on which negative emissions strategies tend to rely most heavily are as yet unproven. What happens if the necessary negative emissions measures ultimately prove technologically infeasible, or cannot be deployed at the necessary scale because of fundamental biophysical constraints? (Type 1 risk in Fig. 1).

Second, even if the necessary negative emissions options are technically feasible, the ecological and social costs may be unacceptably high, preventing the realization of other development goals (Type 2 risk in Fig. 1). Land-based negative emissions options, insofar as they rely on the relatively inefficient processes of biological carbon fixation via photosynthesis, are inherently land intensive. There is no guarantee that it will be possible to deploy them at large enough scales without major adverse impacts on biodiversity, food security, water resources and human rights. It might prove feasible if development and NET-reliant climate trajectories can be well aligned, but there is no assurance of this. It would require further research to understand whether and how synergies can be reaped and trade-offs avoided, and careful planning and governance to ensure effective implementation at large scales across diverse contexts.

Third, even if negative emissions options prove feasible and can be undertaken at large scale without adverse ecological and social consequences, the risk remains that they will prove less effective than expected at reducing climate impacts (Type 3 risk in Fig. 1). In the case of land-based NETs, the risk of reversal is a distinct possibility: carbon sequestered in land is vulnerable to release either through human action (e.g. land clearing) or natural forces (e.g. drought, fire and pests). Irreversible climatic changes could be locked in during the period of concentration overshoot before emissions are brought back down. Impacts that could be wholly or partially irreversible include species extinction, coral reef death, and loss of sea or land ice, some of which themselves lead to positive feedbacks or tipping points that current carbon cycle models do not currently take into account.

Considering these risks, it is critical to assess carefully any strategy that relies on negative emissions. Relying on the future large-scale deployment of negative emissions before we have high confidence that such options will be technically feasible, ecologically and socially acceptable, and reliably permanent and effective cannot be considered an equitable and effective approach to climate mitigation. If we overshoot the available carbon budget with the intention of balancing it with negative emissions in the future, and later learn this is not possible, we will be faced with a much more disruptive transition and greater climate change impacts than we had intended. As expressed by Fuss et al. (2014): "Determining how safe it is to bet on negative emissions in the second half of this century to avoid dangerous climate change should be among our top priorities."

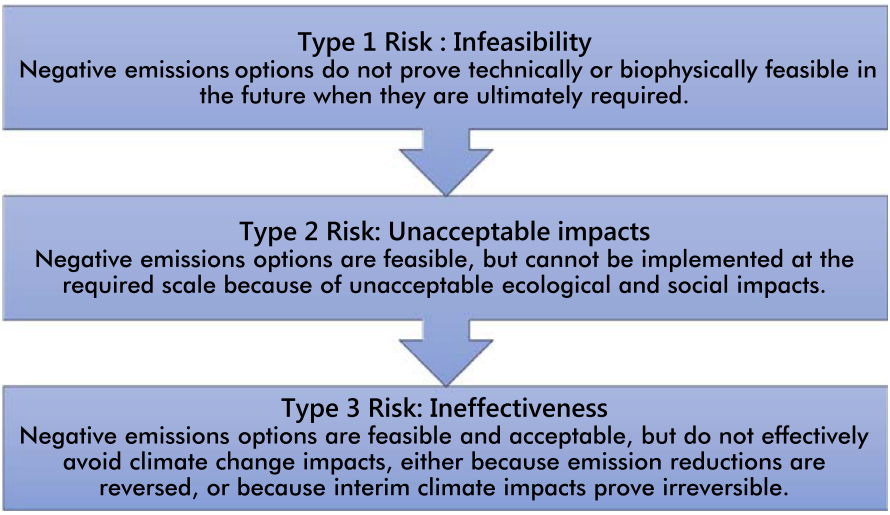

Fig. 1 Three types of risks posed by negative emissions measures

2.2 Applying risk evaluation framework to land-based negative emissions options

This section applies the risk evaluation framework outlined above to specific land-based options for NETs: forest ecosystem restoration; reforestation; and BECCs. We use this evaluation framework to organize a set of questions to comprehensively evaluate risks to successful deployment of land-based NETs (as summarised in Table 1).

Table 1 Risks to successful deployment of land-based NETs

Risks to deployment of land-based NETs		
Technical and biophysical infeasibility	Unacceptable social and ecological impacts	Ineffectiveness
Technological problems and constraints could prevent full-scale BECCS operation	Demand for land could compete with food production and security	Land-based carbon sinks may be prone to reversal, negating mitigation benefits
Sink saturation may limit sequestration potential of NETs NPP may limit expansion of crop production	Demand for land (exacerbated by lack of clear land rights) could cause dispossession of local communities and livelihoods	Temperature overshoot may lead to irreversible impacts, including on food production, and biodiversity, threatening adaptive capacity
Expected yield increases may not be achieved, particularly in the light of climate change	Demand for land could drive loss of natural ecosystems, weakening resilience and adaptive capacity, and result in conversion of forests, wilderness areas and biodiversity Replacing natural ecosystems with monocultures causes loss of biodiversity Increased inputs for energy crops and forests may cause land and water pollution	Temperature overshoot may cross tipping points preventing further temperature reduction

2.2.1 Risk type 1: Biophysical and technological feasibility

Land-based negative emissions options are limited by fundamental biophysical constraints. Sink saturation sets an upper limit on the total cumulative volume of carbon that can feasibly be removed from the atmosphere and stored in the biosphere,[4] and net primary production (NPP) from plant growth sets a limit on the feasible rate of removal of carbon from the atmosphere. The amount of carbon that can be sequestered in the terrestrial biosphere is finite—an assessment of past land-use change indicates an upper theoretical limit to cumulative terrestrial sequestration of approximately 187 GtC before ecosystem sinks would be saturated (equal to total terrestrial carbon loss though past land-use change) (Canadell and Schulze 2014; Mackey et al. 2013). The practical limit is lower, however, because current land uses, including settlements and agriculture, preclude restoring carbon stocks to their previous levels.

Uncertainties around technological feasibility apply mainly to BECCS, which is also most heavily relied on in mitigation scenarios for negative emissions,[5] even though BECCS plants have not been built and tested at scale, and deployment of CCS technology lags substantially behind targets consistent with typical 2 °C mitigation scenarios (Peters et al. 2017). Challenges are also posed by the logistics associated with the long-term reliable supply of biomass feedstock to large-scale industrial facilities, integration of disparate technological systems, the establishment of sufficient and spatially appropriate CCS capture, pipeline, storage infrastructure and reservoir capacity, and ensuring that full life-cycle emissions are indeed net negative (IPCC 2014).

2.2.2 Risk type 2: Unacceptable social and ecological impacts

Land-based negative emissions options on a scale typically considered in long-term mitigation assessments require large areas of productive land, with estimates in the literature ranging from 100 million to almost 3000 million hectares (Mha) (IPCC 2014). The upper end of this range is equal to twice the world's currently cultivated land—even though competition for productive land is already a global concern (Nilsson 2012; Searchinger and Heimlich 2015). Below, we consider risks related to social and ecological impacts in turn.

Social impacts generally relate to the expected scale of land use for NETs. Whether for bioenergy crops, reforestation, or other land-based sinks—large-scale land use can compromise food security by reducing the availability of land for food production (IPCC 2014). Food security has long been a global development priority. Land availability is not the only component of food insecurity, but how land is used and who can access it is a critical factor in achieving global food security objectives.

Dedicated use of land for negative emissions options could displace natural ecosystems and existing land uses that have an important role for subsistence production and sustainable livelihoods for local communities and smallholder food producers. Local communities and indigenous peoples already face increasing threats of dispossession, with

[4] Net carbon uptake in living biomass peaks at around 50–70 years in mature forests, although studies show mature forests continue to sequester carbon in soil and dead organic matter after living biomass saturates (IPCC 2014).

[5] Note that carbon capture and storage combined with fossil fuels cannot lead to negative emissions. Negative emissions are only possible with CCS combined with bioenergy, providing the carbon sequestered exceeds the net life-cycle carbon released from the land conversion, feedstock growth, harvest, transport, processing and usage of the bioenergy, including any ancillary fossil fuel use (See: Searchinger and Heimlich 2015).

around two-thirds of the world's land area under customary or traditional ownership but only a small fraction of that legally recognized (RRI 2015). The lack of clear legal rights to land is a major driver of illegal logging and forest loss, while also enabling large-scale land transfers and displacement that can exacerbate poverty, food insecurity and conflicts. Securing customary local land rights is recognized as an urgent global priority contributing to protecting livelihoods, food security and climate mitigation (RRI 2014).

Ecological impacts are seen primarily though land degradation and increased resource use from land-based mitigation activities such as extensive monoculture plantations for bioenergy crops. Industrial agriculture is already resulting in stress to land and water resources (Alexandratos and Bruinsma 2012). Large-scale deployment of land-based mitigation measures could add to this stress if energy crops lead to significant consumption of the world's fertilizer supply, impacting waterways and ecosystems, and resulting in significant GHG emissions (Smith and Torn 2013). Human perturbation of the nitrogen cycle already causes significant environmental pollution and would need to be reduced by 75% to keep within planetary boundaries (Rockström et al. 2009). Energy crop production may also lead to altering ecosystem function at scale, diminishing biodiversity and depleting scarce resources (Smith and Torn 2013). Biodiversity is now a critical global issue, with species extinction rates at 100–1000 times natural background rates (Rockström et al. 2009).

The scale of the land requirement for NETs suggests serious social and ecological risks, since land plays a crucial role in achieving multiple global sustainability objectives. Given that a large-scale reliance on land use for mitigation may conflict with these objectives (IPCC 2014), these risks need to be well understood before society can be confident that the future large-scale deployment of negative emissions options will be possible (Fuss et al. 2014; Smith and Torn 2013).

2.2.3 Risk type 3: Negative emissions are not as effective as expected

One reason that negative emissions might not yield the expected climate benefit is that carbon stored in the terrestrial biosphere is vulnerable to disturbance. Such carbon storage is thus inherently at risk of reversal. For an ecosystem to serve as a reservoir of carbon, it must remain undisturbed over timescales relevant to climate change (Mackey et al. 2013). Negative emissions options that rely on sequestering carbon into the terrestrial biosphere inherently entail a risk that those carbon stocks will be re-released to the atmosphere. Terrestrial stocks can be lost through both human-induced and climatic factors (land clearing, as well as the sensitivity of terrestrial carbon stocks to drought, pests, fire and other factors). Climate change itself increases the risk of reversals, with projections consistently estimating a weakening of the land carbon sink, potentially undermining the effectiveness of NETs (IPCC 2014; Jones et al. 2016).

Reversals of previously sequestered carbon stocks will negate the mitigation benefit to an extent that depends on the scale of the reversal and the ability of the carbon stock to recover (IPCC 2014). Conversely, stocks of carbon in fossil deposits are stable on geological timescales and not vulnerable to unintended disturbance, therefore avoiding fossil fuel emissions does not present the same risk of unintentional reversal as is posed by sequestration of carbon into the terrestrial biosphere. While BECCS, which utilizes geological storage, is not subject to the same risk of reversal, very small leakage rates may imply the need for continued sequestration into the future, if BECCS is relied on at significant scale (Shaffer 2010).

A second reason why negative emissions might be less effective than expected is the risk that climate impacts occurring during the period of concentration overshoot may prove irreversible. It is known that, for a given amount of total cumulative emissions, peak warming is higher for a pathway that overshoots before negative emissions begin to reduce concentrations. The peak warming is driven by time-integrated radiative forcing and is a function of maximum cumulative emissions (before removals), rather than total cumulative emissions (including removals) (Zickfeld et al. 2012). The higher peak warming causes greater climate impacts, and "increases the likelihood of crossing thresholds for 'dangerous' warming" (Tokarska and Zickfeld 2015). Of particular concern is the potential to pass thresholds relating to sea ice, glaciers, ice sheets and permafrost (ICCI 2015), which can themselves create a positive feedback that causes additional warming (e.g. through albedo effects or methane emissions). The likelihood of irreversible impacts increases with the amount and duration of concentration overshoot (ICCI 2015).

3 Assessing land-based negative emissions options

There is a variety of options for land-based negative emissions, with differing potential impacts on development and climate goals. Ultimately, the extent to which society chooses to rely on these options involves fundamental value judgements. How much risk of overshooting its temperature goal—if the negative emissions options don't work out—is society willing to accept? What risks to other social and ecological objectives is society willing to accept on behalf of those who would suffer the consequences? These questions, clearly, go well beyond mere technical uncertainties. They should be decided within open, transparent, democratic processes, rather than embedded in technocratic modelling exercises.

Here, as an input to such deliberations, we offer an indicative evaluation of three types of land-based negative emissions—forest ecosystem restoration, reforestation, and BECCS, based on the risk evaluation framework. In assessing the potential social and ecological impacts of land-based NETs, we consider three SDGs and key associated targets (Table 2). The SDGs represent a consensus set of global objectives related to development, and it is inevitable that increased demands for land from climate mitigation will affect their

Table 2 Global objectives reliant on land, as defined by selected SDGs

SDG 2: zero hunger	SDG 13: climate action	SDG 15: life on land
End hunger and all forms of malnutrition by 2030	Strengthen resilience and adaptive capacity	Land degradation neutrality by 2020
Double agriculture production and incomes of small-scale food producers by 2030	Integrate climate change measures into national policies and planning	By 2020 halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally[a]
Ensure sustainable food production systems and resilient agriculture practices that maintain ecosystems	Raise capacity for effective climate change actions in LDCs and SIDs, focusing on marginalized communities	Halt the loss of biodiversity[b] Increase the capacity of local communities to pursue sustainable livelihood opportunities

[a]See also the Bonn Challenge, a global effort to restore 350 Mha of the world's forests by 2030. http://www.bonnchallenge.org

[b]Also the CBD Aichi targets to restore 15% of degraded ecosystems and halve the rate of natural habitat loss by 2020

attainment. We have selected the three SDGs that are most reliant on land (although there are clearly others, e.g.: SDG 6), as a starting point for our indicative assessment of the potential impacts that arise from land-based negative emissions. The potential impacts of climate actions on SDGs is a key area for further research, which could build on existing work to explore interactions between SDGs (Nilsson 2017).

We evaluate each NET option as follows: first, we report the proposed or assumed mitigation potential found in mitigation scenarios. We then discuss the potential impacts relative to the selected SDGs based on a review of the literature [SDG impacts (positive or negative) are noted in the text and summarized at the end of this section].

Based on this analysis, in Sect. 4 we provide an indicative estimate of what might be considered a "sustainable" mitigation potential for each NET, considering SDG constraints. Ultimately, as time passes, technologies develop, and socio-economic trends unfold, society will be able to make better-informed decisions about the risks involved and the plausible scale of sustainable negative emissions. In the meantime, presupposing the future availability of much greater quantities is extremely risky.

We begin by assessing the mitigation potential of avoiding emissions from deforestation and forest degradation. Although this does not constitute a form of negative emissions, we examine avoided emissions in the land sector first because these emissions are driven largely by demand for agricultural land (Lawson et al. 2014) and hence could be exacerbated by land-based NETs, and second, because enhancing land carbon stocks is dependent on society's success at reversing forest loss.

3.1 Avoided emissions in the land sector

Just under a quarter of global emissions are from the land sector, with around half of this (approximately 10% of global emissions) coming from land-use change, largely consisting of forest loss in the tropics (IPCC 2014). Reducing emissions from land-use change thus represents significant potential for permanent mitigation benefits. Net global emissions from forest loss (deforestation and degradation) currently average $\approx$ 1.1 GtC/year, although emissions from forest degradation are poorly quantified globally, with recent estimates putting this at almost 70% of overall carbon losses from tropical forests (Baccini et al. 2017). Drained peatlands (organic soils) also cause significant emissions, bringing the total net emissions from land-use change (excluding agricultural soils) to $\approx$ 1.4 GtC/year (Houghton 2013). This represents the maximum mitigation potential from avoiding emissions from land-use change.

Global efforts to reduce and halt forest loss have scaled up significantly in the past decade, largely due to the recognition of the significant climate mitigation potential. While progress has so far been slow, failure to achieve the variety of ambitious targets to halt and reverse forest loss would make the 1.5 °C target more challenging, if not impossible, to meet. Reducing forest loss brings significant benefits aside from carbon. Reducing forest degradation has disproportionately large benefits for biodiversity (Barlow et al. 2016) (SDG 15); intact forests increase resilience to climate change and in many cases increase adaptive and sustainable livelihood capacities for marginalized communities (SDG 13 and 15); and intact forests contribute to sustainable food production through resilient ecosystems (SDG 2). Reducing forest loss also contributes to improved livelihoods for forest communities: research shows that legally recognized tenure rights and local participation in decision-making lead to reduced deforestation and lower CO_2 emissions when compared with forest areas with unclear tenure rights (SDG 2, 13 and 15) (Nolte et al. 2013; Stevens et al. 2014).

3.2 Forest ecosystem restoration

Degraded forests recover naturally over time: forest ecosystem restoration can be defined as enabling or accelerating that recovery. The mitigation potential is significant, because degraded forests store significantly less carbon in the trees and the soil than natural forest ecosystems (Baccini et al. 2017; Mackey 2008).

3.2.1 Unconstrained mitigation potential

Houghton (2013) suggests that forest ecosystem restoration, by protecting and enabling the regrowth of forests, could remove as much as 1–3 GtC/year from the atmosphere, if all harvest of secondary forests and swidden agriculture practices were ended and these lands permitted to regrow.[6] However, because degraded forests vary in the degree of fragmentation and the extent to which biodiversity has been lost, the potential for restoration will vary. Some areas can recover unaided if protected from further disturbance. This is likelier if forest loss is recent, residual trees and soil seed stores remain, and intact forests are still present in the landscape (Lamb et al. 2005). Natural recovery of degraded forests is less feasible where the ecosystem has lost its biodiversity and soils are depleted, making it difficult for plants to recolonize. Enhanced restoration, aimed at re-establishing the original forest ecosystem through cover trees or mixed seeding, is also possible, but is highly resource-intensive, and success often depends on the proximity of nearby native forests to aid recolonization (Lamb et al. 2005). This highlights the immense difficulty of reversing the loss of intact forests.

3.2.2 Impacts on SDGs

Restoration on the scale suggested by Houghton would increase competition over the remaining land, potentially undermining several development goals. Restricting swidden agriculture could have significant impacts on local and subsistence livelihoods, threatening customary access and ownership rights to land (SDG 2 and 15). Moreover, research suggests that shifting cultivation can often be climate neutral rather than emissive, suggesting that climate mitigation efforts targeting these practices might be misdirected (while undermining SDG 15) (Ziegler et al. 2012). Restoring and maintaining intact forest landscapes boost biodiversity, which in turn strengthen the resilience of forest ecosystems to external stressors, including climate change (Thompson et al. 2014), thereby decreasing the risk of reversal of forest carbon stocks (SDG 13 and 15). Yet, there are (limited) mitigation benefits to sustainable harvest of secondary forests—for example, substitution of timber for materials associated with high GHG emissions, such as steel and cement, and storage of carbon in (long-lived) harvested wood products (SDG 15) (Gustavsson and Sathre 2011; Pan et al. 2011). Hence, existing land uses compete with and constrain the potential of ecosystem restoration, while trade-offs exist between different mitigation options.

[6] This carbon sink potential is in addition to "other natural processes on land (that) remove approximately 25% of the carbon emitted each year" (Houghton et al. 2015, p. 1023).

3.2.3 Precautionary mitigation potential

Given these considerations, we argue that a precautionary assumption would be the lower end of Houghton's range, of 1.5 GtC/year in estimating the potential for future carbon sequestration from ecosystem restoration. Achieving this rate of carbon sequestration would still be extremely challenging, requiring a switch from a net carbon source of $\approx$ 1 GtC/year from forests to a net sink of at least the same magnitude. This would require both reversing forest loss and facilitating the effective long-term, stable regeneration of degraded forests.

3.3 Reforestation

Reforestation refers to the re-establishment through human intervention (planting, seeding, etc.) of forest on lands that were forests at some time in the past.[7] This differs from ecosystem restoration in that the land's capacity for natural regeneration has been lost or severely impaired, due to far more intense tree and biodiversity loss and a greater elapsed time since forest clearance. When these areas are replanted, the resulting forests generally have lower biodiversity than a natural forest (Brockerhoff et al. 2008; Lamb et al. 2005), and thus lower carbon storage capacity per hectare (Strassburg et al. 2010). As a result, the total carbon storage per hectare is lower in new forests than in restored degraded forests over timescales relevant to climate mitigation (Mackey 2008).

3.3.1 Unconstrained mitigation potential

Houghton (2013) suggests that reforesting an area of 500 Mha would provide a global sink of $\approx$ 1 GtC/year, which is towards the upper end of the range reported by the IPCC (2014). This land estimate is consistent with mapping of forest landscape restoration possibilities, which identifies 500 Mha of degraded forests and deforested lands that could in principle be restored to closed forests (Laestadius et al. 2011), although there is significant uncertainty around these estimates. In particular, the spatial extent of degraded forests is not well-captured by remote sensing techniques (Baccini et al. 2017), and thus, the degree to which estimates for reforestation potential overlap with estimates for restoring degraded forest ecosystems is difficult to ascertain.

A further 1500 Mha is estimated to be available for 'mosaic' restoration (Laestadius et al. 2011). Mosaic landscapes are defined as accommodating multiple land uses, such as agriculture, protected reserves, managed plantations and agroforestry systems. While the benefits across a range of SDGs from mosaic restoration are large, the climate mitigation benefits are uncertain and difficult to quantify (Lal 2004; Meadowcroft 2013); hence, we do not assume here the future availability of large amounts of atmospheric carbon removal from these activities.

[7] Reforestation here refers to reforesting historically deforested lands, while afforestation refers to establishing forests on landscapes that do not naturally support forests, likely requiring even greater nutrient input. It is worth noting that, while there are many different definitions of forests at international and national levels (i.e.: FAO, UNFCCC), "there is no internationally agreed definition of what a forest is, and the understanding of this term is highly context-specific" (CBD 2012, p. 5).

3.3.2 Impacts on SDGs

The ecological and social implications of closed canopy reforestation on such a large scale would depend on whether the potential impacts are proactively addressed as these projects are planned and implemented, including the choice of sites, how projects are structured (commercial vs. community-based), and the extent to which local stakeholders are engaged. Biodiversity potential varies enormously depending on methods of reforestation, with faster growing species requiring significant nutrient and water inputs that can cause ecological damage and alter local hydrological patterns (undermining SDG 15) (Lamb et al. 2005; Smith and Torn 2013). Reforestation of mixed native species and in carefully chosen sites, on the other hand, could increase biodiversity and restore waterways, reducing run-off and erosion (SDG 2, 15) (Lamb et al. 2005). In addition, the climate effects of reforestation show significant geographical variation; at high latitudes, warming due to reduced albedo can potentially outweigh the benefits of carbon sequestration (SDG 13) (Arora and Montenegro 2011).

3.3.3 Precautionary mitigation potential

In the light of these considerations, it may be reasonable to assume that realistic reforestation extent may be well below the upper bound of the 500 Mha that Laestadius et al. (2011) estimated to be available for closed canopy reforestation through a global ecological mapping exercise that neglects these considerations. It is also important to note that reforestation efforts are driven solely not only by the desire to maximize carbon sequestration, but also by broader social and ecological benefits that can be generated. Localized decision-making can promote multiple objectives and reduce the risk of adverse impacts. The benefits of community-managed and -owned forests are well documented: reforestation programmes which place communities at the centre of efforts can help to secure livelihoods, conserve biodiversity and reduce conflict, while also storing carbon (contributing to SDG 2, 13, 15) (RRI 2014; Stevens et al. 2014; Persha et al. 2011). We take the "Bonn Challenge", a high-level political goal of restoring 350 Mha of degraded and deforested lands by 2030 (consistent with SDG 15), as a more realistic multi-objective target reflecting the relevant ecological constraints.

3.4 Bioenergy with CCS (BECCS)

This section reviews the potential for negative emissions from bioenergy combined with carbon capture and storage (BECCS). As outlined in Sect. 2.2, one constraint on BECCS is the uncertainty of the application of CCS technologies to biomass. This section focuses on a second limiting factor—the availability of biomass supply.

3.4.1 Unconstrained mitigation potential

A key determinant of bioenergy potential is the maximum biospheric capacity of net primary production (NPP) of plant growth. Humans currently harvest just under a quarter of maximum NPP for food, feed, fibre and energy, with the remainder contributing to natural, protected, and cultivated areas (Haberl et al. 2013). NPP therefore limits the production of primary biomass feedstock supply. Based on the remaining NPP in land ecosystems, as well as bioenergy from residues and wastes, an upper biophysical limit in

primary bioenergy supply has been estimated at a similar amount as current human harvest: ≈ 250 EJ/year (Haberl et al. 2013; Kolby Smith et al. 2012). Note this is not an estimate of what could be considered sustainable primary bioenergy potential. Rather, it provides an upper biophysical limit on potential agricultural output (Haberl et al. 2013). In practice, reaching 250 EJ/year in bioenergy output would require more than a doubling of current human biomass harvest (all crops, feedstock and other materials) (Haberl et al. 2013).

Nevertheless, while some estimates of bioenergy potential in mitigation scenarios are well within this upper limit, many are close to or exceed it, with some prominent studies estimating as much as double this amount, and outliers in excess of 500 EJ/year (IPCC 2014). This sanguine outlook on future bioenergy availability has been adopted by many widely cited integrated assessments (as noted by Wiltshire and Davies-Barnard 2015). Creutzig et al. (2015) noted that beyond 100 EJ/year by 2050, there is decreasing agreement on the *technical* potential of bioenergy. The *sustainable* potential can of course be assumed to be much lower.

These estimates for bioenergy are typically based on two sources of biomass: energy crops (including woody biomass) requiring dedicated use of land, and bioenergy sourced from residues and wastes. Bioenergy from residues and wastes includes the utilization of forest and agricultural residues, and organic wastes. Primary bioenergy production is currently ≈ 55 EJ/year, mostly from residues and traditional biomass uses (Erb et al. 2012; Haberl et al. 2013).

3.4.2 Impacts on SDGs

Additional bioenergy production at or above current human harvest of biomass suggests the potential for serious social, economic and ecological constraints on bioenergy feedstock production at this scale (undermining SDG 2, 15) (Haberl et al. 2013; Searchinger and Heimlich 2015). Bioenergy production from forest harvest has been shown to lead to increased emissions (Holtsmark 2015), as could bioenergy crops that require high fertilizer input, or that lead to conversion of wilderness areas (directly or indirectly) (Kolby Smith et al. 2012). Bioenergy has been identified as an emergent global risk to food security and ecosystems due to indirect land-use change (undermining SDG 15). In worst cases, emissions from land-use change could exceed the potential climate mitigation value of BECCS on relevant timescales (undermining SDG 13) (Wiltshire and Davies-Barnard 2015).

Dedicated crops for bioenergy would be likely to increase demand for key resources such as fertilizer and freshwater irrigation, resulting in increased GHG emissions, nutrient loading, watershed stress and environmental degradation (Erb et al. 2012; Smith and Torn 2013). Evidence suggests that even comparatively low levels of bioenergy production (currently at around 5 EJ/year from dedicated land use) have contributed to rising food prices (undermining SDG 2) (Hochman et al. 2014). Deriving bioenergy from wastes could limit land demand, but the availability of residues and wastes for bioenergy is limited by competing uses. Agricultural residues are key to retaining soil carbon in many areas, and forest residues left in place improve biodiversity, soil health and carbon storage. Thus, wastes and residues can be key to meeting other development goals, representing a trade-off with bioenergy feedstock potentials.

Land availability problems often do not arise in models because bioenergy crops are assumed to utilize degraded land, although there is large uncertainty around the scale, spatial location and existing uses of degraded land (Gibbs and Salmon 2015). Models also

circumvent land availability constraints through assumed continued growth in crop yields, delivering greater bioenergy productivity or freeing up agricultural land for energy crops. However, the growth of crop yields has slowed down considerably in recent years (Alexandratos and Bruinsma 2012). Dramatic yield increases in the past were mainly achieved by increasing the "harvest index", i.e. shifting biomass production to the grain portion of the plant at the expense of the stem portion, hardly changing total biomass production. This does not benefit bioenergy feedstock production, in which the whole plant is used. Improving bioenergy feedstock production would rely on other strategies, such as improving basic photosynthetic efficiency or overcoming stubborn yield gaps, which cannot be taken for granted (Kemp-Benedict et al. 2012). Potential for yield increase has commonly been overestimated in assessments of future bioenergy potential due to extrapolation of plot-based samples (Kolby Smith et al. 2012). It is also possible that any future yield increases will be needed to help meet growing demand for food (SDG 2) (Alexandratos and Bruinsma 2012; Searchinger and Heimlich 2015).

However, potential demand-side measures exist for reducing the agricultural land requirements, such as diet change, by reducing demand for land-intensive commodities (SDG 15) (Nilsson et al. 2012). Although in recent decades, diets have shifted towards more land-intensive meat-rich diets as incomes have risen, diets could shift in the future in a manner that frees up agricultural land, with the potential to reduce net GHG emissions from agriculture and land use by about 45% due to decreased reliance on livestock (SDG 13) (Bajželj et al. 2014).

3.4.3 Precautionary mitigation potential

Key uncertainties in total bioenergy potential therefore lie in the availability of land for dedicated energy crops; the potential for yield increase; and trade-offs with other land uses such as food production and biodiversity. While it could happen that a combination of yield improvements and diet changes could make more land available for bioenergy feedstock production, it would not be prudent to presuppose that this will occur and to expect land to be available for future climate mitigation. Deploying bioenergy on any scale, even well below the estimates in many climate models, would require effective global governance networks to manage trade-offs and the development of integrated land-use policies to ensure sustainable land use (Nilsson 2012). Climate change itself also introduces further uncertainty into bioenergy potential (IPCC 2014).

A precautionary perspective in the face of land availability constraints and the possible negative impacts of large-scale expansion of bioenergy production on food security and ecosystems, would suggest that it is highly risky to rely on the future availability of significant amounts of land for producing biomass feedstock for BECCS. In a carbon-constrained world, the effective use of wastes and residues should be prioritized, which would enable bioenergy at fairly limited scales, and possibly with no CCS (Miyake et al. 2012). Confidence that bioenergy can be deployed at significant scale as a negative emissions measure would be warranted only after feasibility of the required technologies is proven and robust institutions and practices for scaling up bioenergy feedstock production without posing unacceptable ecological and social costs are developed. As noted by Haberl et al. (2013), "Identifying sustainable levels of bioenergy… remains a huge and pressing scientific challenge." Until then, it is risky to base current mitigation strategies on the presumed future availability of large-scale bioenergy with CCS (Table 3).

Table 3 Synergies and trade-offs between land-based NETs and SDGs

NETs	SDGs		
	SDG 2: zero hunger	SDG 13: climate action	SDG 15: life on land
Avoided deforestation	+ Resilient ecosystems, sustainable food production for local communities	+ Avoided emissions + Increased resilience + Secure tenure, greater forest protection	+ Disproportionally large benefits to biodiversity + Sustainable livelihoods
Reforestation	+ Careful restoration can reduce environmental degradation, improve ecosystem resilience and food production − Quick-growing species can increase nutrient input	+ Significant mitigation potential from closed canopy reforestation − Reduced albedo effect at high latitudes	± Biodiversity impacts vary dependent on method of reforestation + Community-managed reforestation has greater livelihood, climate and biodiversity benefits
Forest ecosystem restoration	− Livelihoods threatened if subsistence ag. targeted + Resilient ecosystems, sustainable food production for local communities	+ Greater carbon density, increased mitigation potential + Increased resilience − Climate benefits reduced if (traditional) subsistence ag. targeted, or HWP[a] overly restricted	+ Correlation between carbon density and biodiversity − Local access threatened if subsistence ag. targeted − Constrained by existing land uses
BECCS	− Dedicated use of land for bioenergy competes with land for food production − Use of residues for bioenergy can reduce soil carbon, lowering productivity	± Carbon neutral bioenergy (hence negative emissions from BECCS), only if sequestered carbon exceeds net emissions (including initial and indirect land-use change emissions)	- HANPP[b] for bioenergy can compete with food, biodiversity and subsistence livelihoods − Large-scale bioenergy increases input demand, resulting in environmental degradation and water stress

[a]Harvested wood products

[b]Human appropriation of net primary production

4 Magnitude of "sustainable NETS"

Based on the analysis of various land-based options for NETs in Sect. 3, Table 4 presents a set of options for achieving 370–480 Gt CO_2 in carbon removal that may not exceed biophysical constraints, and could conceivably—though by no means guaranteed—be implemented in a manner that achieves the required amount of negative emissions without jeopardizing other critical land uses and sustainable development objectives. Achieving this level of NETs would still be extremely challenging to achieve and would impose a demand for land that could jeopardize other critical land uses such as food production, habitat, and biodiversity, and thus present serious risks if not implemented with strong governance, legal and human rights oversights.

As a convenient reference point for the state of scientific knowledge and integrated assessment model results on temperature targets and global mitigation pathways, and the corresponding analysis on the role of negative emissions mitigation measures, we draw upon analysis by Rogelj et al. (2015), which shows that the range of expected negative

Table 4 Constrained negative emissions potential

Negative emissions category		Cumulative sequestration (21st c.)
Reforestation	This case assumes optimistic levels of reforestation consistent with meeting the Bonn Challenge to reforest 350 Mha by 2030. Assuming a per hectare sequestration rate consistent with Houghton (2013) yields an average negative emission rate of 0.7 Gt C/year. Over a period of 60 years until saturation, this would yield cumulative negative emissions of 40 Gt C	150 Gt CO_2
Forest ecosystem restoration	Extensive ecosystem restoration, sufficient to enhance the natural sinks at an average rate of 1 to 1.5 Gt C/year for 60 years until saturation, would yield cumulative negative emissions of 60 to 90 Gt C	220–330 Gt CO_2
Bioenergy with CCS	Negative emissions from BECCS are deferred until uncertainties are resolved, especially regarding technological feasibility and land availability, and the need for effective institutions to protect socio-economic and ecological objectives such as food and water security. This is on the basis that the full technological system is not yet proven, and that BECCS would be able to contribute at significant scale only if undertaken in a way that does not undermine other social and ecological goals	Deferred
Total		370–480 Gt CO_2

Nb: Units in the middle column are given in GtC, as this unit (or the equivalent PgC) is most commonly used in literature related to terrestrial carbon fluxes. Units in the cumulative mitigation potential column are given in Gt CO_2, as this more readily relates to policy discussions. The conversion is given by 1 GtC = 3.67 Gt CO_2

emissions from published 1.5 °C scenarios is between 450 and 1000 Gt CO_2, and for the 2 °C scenarios, between 0 and 900 Gt CO_2, cumulative over the course of this century. In these scenarios, negative emissions measures are adopted widely in the second half of the century to reverse a large fraction of cumulative future fossil fuel emissions (up to 60% in the 2 °C scenarios, and as much as 100% in the 1.5 °C scenarios). Our analysis here suggests that the upper end of the stated range of negative emissions must be called out as improbably high, given biophysical limits and the risks of social and economic impacts.

However, a large number of the modelled 1.5 °C (and 2 °C) pathways at the other end of the range require significantly lower levels of negative emissions. In fact, a total of 480 Gt CO_2 would be sufficient to meet the negative emissions needs of more than one-third of the modelled 1.5 °C scenarios, an amount which could potentially be met with more sustainable options for negative emissions.

5 Conclusion

The Paris Agreement recognizes the urgency of responding to climate change and commits nations to doing what it takes to keep warming well below 2 °C and aiming for 1.5 °C. If the promise of future negative emissions leads policy makers to grossly underestimate the effort needed in the near term to meet these targets, the results would be disastrous. The decades during which society had allowed itself a slower, softer transition would

eventually be revealed as an unaffordable loss of time during which the only effective strategy would have been rapid emission reductions. Saddled still with a fossil fuel-dependent energy infrastructure, society would face a much more abrupt and disruptive transition than the one it had sought to avoid. Having exceeded its available carbon budget, and unable to compensate with negative emissions, society could ultimately be faced with much greater warming than it had prepared for. An inadequate response to the climate crisis, based on an unfounded assumption that BECCS or other measures can be used to "undo" emissions at a later date, would be woefully irresponsible and dangerous. Such a strategy could leave us—and future generations—stranded with an insufficiently transformed energy economy and a carbon debt that cannot be repaid. Ultimately, to ensure equitable climate mitigation pathways, policy choices must be governed by the objectives of sustainable development, which in the land sector provides the opportunity for important synergies between land, food and climate goals. These choices are fundamentally value-laden, relating as they do to our willingness to accept risks and how we choose to distribute the consequences among populations and generations. These profound choices fall in the domain of public discourse and political processes, rather than technocratic exercises.

As an input to such deliberations, we provide here a framework for understanding the risks and potential consequences, and an indicative assessment of the potential for negative emissions that may be more consistent with broader sustainability goals. This analysis suggests that measures such as ecosystem restoration and reforestation may possibly be able to achieve the carbon drawdown required for 1.5 °C, if the protection and restoration of carbon-dense and biologically rich natural forests are prioritized as a critical mitigation strategy. In addition to contributing to substantial climate change mitigation, such options contribute to a multitude of sustainability objectives, including preserving ecosystem services such as biodiversity and watershed protection, and development goals of food security, human rights and local livelihoods. Indeed, the second half of the Paris Agreement mitigation goal states that the "balance" must be achieved "in the context of sustainable development and efforts to eradicate poverty" (Article 4.2). Achieving these dual outcomes of climate and development goals will require political choices that maximize synergies between climate mitigation and broader development objectives.

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Chapter 7

Conclusions

This chapter summarizes the results and answers the thesis' core question and three subsidiary research questions. Here I show how Chapters 4, 5 and 6 trace the development of land-based mitigation in the international climate regime, and how governance by expertise results in policy directions in global climate governance that lack consideration of broader societal objectives around sustainable development. Chapter 4 showed how a governance by expertise approach to land in the Kyoto Protocol via technical accounting rules set the stage for a central role for land-based mitigation in the Paris Agreement. Chapter 5 employed a co-production analytical lens to look at how negative emissions came to be legitimized in future mitigation pathways, and the implications of this for food security and biodiversity objectives. Chapter 6 examined the impacts of different options for land-based negative emissions, presenting a normative evaluation of carbon-dioxide removal options that have the potential to both balance sources and sinks, while also contributing to sustainable development.

The rest of this chapter proceeds as follows. After presenting key findings from the three research chapters in section 7.1, I then consider the limitations of this study in section 7.2 and make suggestions for future research in section 7.3. I conclude in section 7.4 that an understanding of the politics of expertise and the co-production of science and policy can inform an understanding of the limits to terrestrial carbon removal, and the need to look for alternative mitigation options aligned with broader societal justice objectives.

7.1 Key findings

The following discussion integrates the findings from earlier chapters to illuminate how a technocratic approach to land-sector governance can lead towards policy outcomes that represent significant trade-offs with broader societal objectives as expressed in the SDGs. This discussion is focused around four over-arching themes - governing by expertise; limits to terrestrial carbon removal; the risks of relying on negative emissions; and alternative, more socially just, options for land-based carbon mitigation. The analysis in earlier chapters is reliant on a critical approach to evaluating the disproportionate power of certain social roles within social structures or institutions on the construction of knowledge, and how some value-based assumptions are promoted at the expense of others.

7.1.1 Governing by expertise

This section answers the first research question: How is terrestrial carbon science co-produced with policy demands in the context of land-use in current and future mitigation pathways?

Chapter 4 analyzed the contested politics of including (and accounting for) land-based mitigation in the Paris Agreement. The Chapter outlined how, under the Kyoto Protocol, technical debates over land-use accounting rules served as a site of politics in setting targets for countries. The findings pointed to a number of specific characteristics that were central to the governing (and disciplining) of expertise in negotiations leading to the Kyoto Protocol, and subsequently the Paris Agreement - in particular the focus on fungibility to allow for a 'net' accounting system. While net emissions are what matters for temperature targets, it is the accounting of gross emissions that provides policy incentives to reduce emissions in the land sector, rather than offsetting one mitigation opportunity for another. I relate this analysis of governing expertise and governing by expertise to Barnett and Duvall's (2005, p.62) example of indirect expressions of power (institutional and productive), which concern "not who governs, but instead how the governing capacities of actors are produced, how those capacities shape governance processes and outcomes,

and how bodies of knowledge create subjects that are to be, at least in part, self-regulating and disciplined".

The conflicts over inclusion of LULUCF in the Protocol were due in part to abiding contestations over the assumption of fungibility. That is, the political assumption was made that avoided emissions and removals from the land sector were interchangeable with emission reductions from fossil fuels based on the selective evoking of scientific knowledge. Complex land-use accounting rules were developed to make it easier for countries to meet their mitigation obligations. Due to sustained scientific critique and persistent debates around the efficacy and mitigation potential of terrestrial sinks, ultimately the inclusion of LULUCF in the Protocol required a *disciplining* of scientific knowledge, in that sequestration science (i.e., the science of removing emissions through terrestrial sinks) was selectively evoked by policy experts in this realm to align knowledge with a politically desired outcome – crediting the use of sinks against national climate targets. I characterized this as 'governing expertise', where science was selectively evoked or discarded to support the political positions of parties in the final stages of the negotiations under the Kyoto Protocol, thereby disciplining the use of expertise in the political setting.

Following on from the 'disciplining of expertise' that paved the way for the inclusion of sinks in the Protocol, was 'governing *by* expertise' in the technical negotiations to allow fungibility between terrestrial and industrial emissions in the accounting rules of the Protocol. This saw LULUCF negotiators, themselves experts in sequestration science, employing complex arguments about the intricacies of accounting for terrestrial emissions and removals, yet doing so in a way that suited the specific circumstances of different countries, hence governing by expertise. Key to this was the contested process of negotiating baselines, against which to measure progress in reducing land-sector emissions, in a manner that was politically palatable but also scientifically defensible in the net accounting system of the Protocol.

These political decisions on including land-based mitigation in the climate regime, accompanied by a selective evoking (or ignoring) of scientific disputes over fungibility, shaped future negotiations on LULUCF accounting rules in the Protocol. Following this line of enquiry through to the Paris Agreement saw similar dynamics at work. Indeed, the language used to include land in the Protocol - ‘‘net changes in greenhouse gas *emissions by sources and removals by sinks’’* (United Nations 1998, Article 3.3 , italics added) - was adopted in the Paris Agreement to form the long-term mitigation objective, minus the constraints around land-use mitigation that were included in the Protocol to make the inclusion of sinks politically acceptable. The Paris Agreement’s long-term mitigation objective reads: “to achieve a balance between anthropogenic *emissions by sources and removals by sinks* of greenhouse gases” (United Nations 2015, Article 4.1 , italics added). While path-dependency no doubt played a role in the adoption of previously accepted language, the context of including sinks in the Agreement was very different. Land-based mitigation had moved from being a politically contested add-on in the Protocol to occupying center stage in the long-term mitigation goal of the Paris Agreement.

A further consequence of the political acceptance of fungibility and the use of net accounting practices was the emergence of the idea of ‘net-zero’ as the Agreement’s long-term mitigation goal. Indeed, the phrase ‘balancing sources and sinks’ has been interpreted to mean the same as ‘net-zero emissions’, which implies that terrestrial sinks are both fungible with, and will be used to offset, ongoing (industrial and terrestrial) sources of emissions. The language of net-zero was introduced to the UNFCCC discussions after the IPCC Fifth Assessment Report included long-term mitigation pathways that relied heavily on assumptions of ‘negative emissions’ (IPCC 2014). This can be seen as an example of governance *by* expertise, where political acceptability is achieved through the institutional power lodged in climate science. Rather than exerted through the IPCC as a form of structural or institutional power, this can be seen as an expression of productive power, where the enacting of boundaries from both science and policy experts mutually constitutes the authority

of scientific knowledge. I argue this results in a technocratic governance of land-use in the climate regime – governance by expertise.

These findings highlight how global climate governance is now critically dependent on large-scale carbon removal via terrestrial sinks. The introduction of sinks into the Kyoto Protocol paved the way for this, making developed country targets easier to meet through a selective disciplining and evoking of sequestration science – the twin processes of governing (disciplining) expertise, and governing *by* expertise. Constituted through political negotiations and the shaping of sequestration science, complex accounting rules were designed to both permit and limit the degree to which terrestrial sinks could be used to offset industrial emissions. The introduction of land-based sinks as 'negative emissions' to achieve the 'net-zero' goal of the Paris Agreement, can be seen as a continuation of this expert led approach to climate governance. Governing expertise sees the evoking of scientific knowledge for political ends, while governing by expertise sees morally charged and contested issues dealt with in a technical setting, obscuring underlying normative assumptions. In the Paris Agreement, the political objective is no longer to limit the use of terrestrial sinks, but instead to increase and maximize opportunities for their use. In a post-2020 climate regime, where land is expected to play a more prominent role, any approach to mitigation that focuses on 'net' emissions (i.e., emissions minus removals) while obscuring the politics hidden in land-use accounting runs the risk of not delivering the required climate mitigation but also, through governing by expertise, of obscuring important normative choices over future societal objectives.

7.1.2 Co-producing climate science-for-policy

This section answers the second research question: How have land-based negative emissions been legitimized as key mitigation options under the Paris Agreement?

The preceding section used the twin concepts of governing by expertise, and disciplining expertise, to explore the use of science in policy-making around the inclusion of land-use in global climate governance. In this section, I recount how Chapter 5 used a more in-depth analysis of the concept of co-production between climate modellers and policymakers to explain how model results are produced, gain authority, and are institutionalized in global climate governance. The use of co-production as an analytical framework allows us to go beyond the essentially adversarial relations of power described by Barnett and Duvall (2005), to explore the mutual constitution of knowledge and social relations and its potential for a cooperative function.

Key questions of governance and accountability arise in the use of IAMs for determining policy options for mitigation pathways compatible with the Paris Agreement. There is an established body of literature in STS which critiques climate models as a site of knowledge production, resulting in a technocratic policy orientation that obscures values and political choices which deserve wider debate. The examination of IAMs in Chapter 5 found this critique to be highly relevant, as IAMs originally designed for exploratory research ('what climate outcomes would future policy scenarios produce?') were being applied as decision-making tools ('what are the policy responses needed to reach agreed-upon temperature targets?'). This shift from predictive to determinative in the use of IAMs gives model-based knowledge considerable authority in climate policy development.

When looking at how modelled outputs are co-produced with policy demands, I found that the perception of model-based knowledge as 'objective science' lends authority to outcomes that might otherwise be more critically debated and contested. The enacting and maintenance of boundaries between 'facts' and 'values', to confer model results with scientific authority, was demonstrated through a number of practices of the modelling community.

First, the treatment of empirical uncertainty in IAM baseline assumptions is dealt with in a way that combines "elements of scientific evidence and reasoning with scientific and political judgment" (Jasanoff 1990, p.229), demonstrating a hybrid approach typical of regulatory science.

Second, in tracing the history of IAMs, I found that large scale negative emissions, in the form of BECCS, were introduced to models on the basis of technological (existence of the technology and cost assumptions) rather than real-world feasibility. This occurred despite concern from policy experts about the potential impacts of the scale of bioenergy and land-use change assumed in the models. Yet modellers were found to be reluctant to introduce 'real-world' constraints to achieve a desired output, considering the corruption of modelling assumptions by such social and political considerations to be 'unscientific'. This reluctance to include societal objectives as baseline constraints can be seen as a form of boundary work, defining IAMs as objective science that confers results with "unshakeable authority" (Jasanoff 1990, p.236). Yet Chapter 5 finds the scale of modeled 21st century land-use change for bioenergy-driven climate mitigation exceeds what may be considered sustainable with relation to food production needs and biodiversity protection.

IAMs, drawing on the power of scientific practice as a legitimizing authority, can be seen to have had substantial policy impacts leading up to the Paris Agreement, and continue to have significant influence in international and national climate policies. Hulme (2011) terms the disproportionate power model-based descriptions wield in political and social discourse around climate futures 'climate reductionism'. While IAM scenarios generate valuable knowledge for climate policy, paradoxically, the intention for modelled scenarios to be non-policy prescriptive is undermined if negative emissions reliant pathways are used to justify less stringent near-term targets. The 'lock-in' potential of mitigation pathways reliant on large-scale carbon removal requires more critical examination by decision-makers and other stakeholders. Highlighting the shift from predictive to determinative use of models could open the way for more responsible knowledge production.

These findings speak to a similar dynamic as was discussed in the preceding section - the twin processes of governing expertise (political considerations disciplining science) and governing by expertise (technical processes used to obscure political motivations). First, the inclusion of negative emissions in low emissions scenarios can be seen as a form of governing expertise, where policy demand for low emissions scenarios drove the inclusion of negative emissions. Second, the

legitimization of IAMs as key inputs into the political process can be seen as a form of governing by expertise – a technical and scientific process is used to embed "contestable normative assumptions within scientific authority" (Dooley et al. 2018, p.8), obscuring the underlying value-based and ethical choices inherent in any scenario-building exercise.

Based on the conceptual framework for critical knowledge production outlined in Chapter 3, I conclude that IAMs represent an illegitimate process of co-production, where questions are narrowly framed and exclude key social considerations. These findings highlight the need for political debates to make explicit the values and assumptions embedded in the co-production of science and policy - broadening, rather than narrowing, the scope of policy options. Closer engagement between modellers and policy experts for mitigation scenario development would allow for more negotiated forms of knowledge production, which might better clarify and represent the multiple objectives and interests at stake in the utilization of limited land resources. This would represent a more transparent expression of power through an explicitly normative approach to co-production, enabling processes to be contested and debated by key stakeholders when necessary, rather than uncritically legitimized in policy pathways.

It is worth noting that a more self-reflective attitude can be seen to be emerging on the part of integrated assessment modellers, as outlined in Section 5.2. Here, we see what I suggested above – that a more informative set of mitigation scenarios could be produced by explicitly including social and environmental goals in models, and contrasting the use of these 'constrained' and 'unconstrained' scenarios in the scientific and policy-oriented literature. This can be seen as an example of Jasanaoff's 'serviceable truth' – a negotiated model of regulatory science that "commits scientist, no less than other actors, to moderating their views toward a societal mean" (Jasanoff 1990, p.250).

7.1.3 Limits to terrestrial carbon-dioxide removal

This section answers the third research question: What are the outcomes of a technocratic approach to terrestrial carbon mitigation, and what are the potential implications for sustainable development objectives?

Following the earlier discussion on the co-production of science and policy (through governing expertise, governing by expertise, and through a (normatively) illegitimate use of scientific authority), I now turn to an examination of the resultant policy outcomes that flow from this expert-led approach to governance in future mitigation pathways.

As demonstrated, modelled climate mitigation pathways for lower temperature limits almost universally rely on large volumes of 'negative emissions' to remove carbon from the atmosphere. This is achieved predominantly through the use of BECCS, which relies on the conversion of extensive areas of land to this end, raising concerns over trade-offs with sustainable development objectives. In order to asses these potential trade-offs, I used the SDGs as a set of societal objectives agreed by the international community. Of these, I chose three SDGs with particular relevance to land – SDGs on food, land and climate - with specific objectives against which to assess the potential impact of negative emissions.

The language of net-zero emissions, mainstreamed in the policy debate through the Paris Agreements objective to balance sinks and sources, does not impose any limit or cap on the use of terrestrial sinks. Modeled mitigation pathways are assumed to be reliant on the large-scale use of terrestrial sinks, effectively to the extent needed to balance the carbon budget. This strategy poses fundamental risks to the realization of low emissions pathways, due to uncertainties about whether society will ultimately be able to realize the benefits of negative emissions when they are needed, as well as risks to development objectives, due to potentially unacceptable social and ecological impacts of negative emissions. Considering these risks, it is critical to assess carefully any strategy that relies on negative emissions. Lövbrand (2004), in calling attention to the risks of over-reliance

on sinks in the Kyoto Protocol, draws on Beck's concept of reflexiveness (a more self-reflexive attitude) towards policy decisions legitimized by scientific results. In *Risk Society*, Beck suggests that modern society needs to acknowledge the limits to scientific enquiry and move towards new forms of rationality (Beck 1992). Others argue that accepting the basic character of uncertainty in complex ecological systems would result in different policy conclusions than if indeterminacies are presented as 'deterministic certainty' (which allows prediction, management and control to be maintained) (Holling 1993, Wynne 1992, in Keeley & Scoones 2003, p.29).

In Chapter 6, I proposed that the objectives of sustainable development are critical to the land sector, given the opportunity for important synergies between land, food and climate goals. Returning to Jasanoff's concept of 'serviceable truth', Chapter 6 developed an indicative assessment of the realistic potential for land-based NETs, based on a precautionary assessment of the risks to their future effectiveness and a provisional assessment of the extent to which they are in conflict with sustainable development goals related to land, food and climate. In line with the idea of normatively legitimate and illegitimate co-production, as outlined in the preceding section, Chapter 6 establishes an explicitly normative framework to evaluate negative emissions against potential synergies and trade-off with SDGs reliant on land. Here the questions were broadly framed to incorporate socially-sanctioned objectives.

In this way, rather than leaving the co-production of science and policy unacknowledged, and relying on scientific authority for credibility of outcomes, this approach derives credibility from the socially sanctioned parameters used to determine outcomes. These choices are fundamentally value laden, relating as they do to our willingness to accept risks and how we choose to distribute the consequences among populations and generations. Making such choices falls in the domain of public discourse and political processes, rather than technocratic exercises.

Chapter 6 found options to achieve the CO_2 removal required for 1.5 °C mitigation pathways that may not exceed biophysical constraints, and could conceivably be implemented in a manner that

achieves the required amount of negative emissions without jeopardizing other critical land uses and sustainable development objectives. Measures such as ecosystem restoration and reforestation could, in addition to contributing to substantial climate change mitigation, contribute to a multitude of sustainability objectives, including preserving ecosystem services such as biodiversity and watershed protection, and development goals of food security, human rights and local livelihoods. Achieving the dual outcomes of climate and development goals reflected in Article 4.1 of the Paris Agreement requires political choices that maximize synergies between climate mitigation and broader development objectives.

7.2 Limitations to study

The aim of this study was to conduct so called 'theory-driven research', where the primary intention was to apply theory to current policy problems, rather than to advance a particular theoretical approach. Each of the research chapters relied on empirically derived data – notably interviews, participant observation and content analysis of policy documents. In terms of the research carried out, the relatively small number of interviews conducted could be considered a limitation - on the other hand, interviews were well-targeted at key experts in the field of enquiry, reducing the need to cast a wide net.

This work took a deliberately global scope, focusing on the 'micro' governance elements of the role of land in the climate regime, within the 'macro' governance context of global climate governance. Urgently needed is work in this area focused more on spatially explicit issues, given the local contexts and situations that would give rise to the issues discussed in Chapter 6 (where are carbon sinks proposed, whose land is it, what are the existing land uses, what is the sequestration potential, are there biodiversity impacts?). Much of the land expected to be used for negative emissions is categorized as marginal or degraded; areas where a lack of clear customary and collective rights to land make people vulnerable to dispossession in the face of increasing demand for land (Dooley 2018). An understanding of the global scale issues, in how a reliance on land-

based sinks has been legitimized as a central strategy of global climate governance, is an important first step to enrich approaches to addressing locational specific studies.

Finally, this study occurs in the context of a rapidly moving field of politics and science. The conclusion of the Paris Agreement, which happened during the first year of this research, brought an unexpected focus to 1.5 °C pathways, and with that, an increase in the use of, and attention to, the reliance of negative emissions for deep mitigation scenarios. One of the outcomes of the Paris Agreement was a request to the IPCC to produce a Special Report on 1.5 °C pathways. With the deadline for publications to be accepted into this IPCC report occurring around the same time this thesis was being finalized, resulting in an avalanche of publications over the final six months of this work - all of high relevance to the research questions proposed here. These have been included wherever possible, but conducting a study on an 'emerging epistemic battle' during the time of emergence, is in itself both a fascinating experiment, and a severe limitation on viewing the site of study with some distance.

7.3 Next steps and future research

IAMs have given us critical insight into the scale of mitigation ambition required to achieve the temperature objectives of the Paris Agreement, but due to limitations of integrated assessment, have also sought to rely on a deployment of negative emissions technologies that are likely to prove unachievable in the real world. The mitigation actions that could be taken to minimize the reliance on negative emissions, and the level of negative emissions that could realistically be achieved are areas for further research.

Determining how to effectively achieve this (where / when / who / how) is not a technical question, but is critically reliant on governance and oversight. Specifically, this will require:

- The potential impact of climate mitigation actions on SDGs is a key area for further research, which could build on existing work to explore interactions between SDGs (c.f. Nilsson 2017).
- Implications of different accounting options for negative emissions. The need to separate fossil from terrestrial carbon accounting, in order to understand the gross carbon fluxes will be critical to properly incentivize a shift in anthropogenic terrestrial emissions from a net source to a net sink. This could be achieved through both simplifying and improving the robustness of land sector accounting by focusing on IPCC reporting guidance and separating accounting regimes and targets for industrial and land-based CO_2 emissions to ensure removals are net-negative.
- Concrete interventions to improve governance of the land sector, and to align climate mitigation activities with SDGs.

There is increasing recognition of the need to combine other disciplines with natural science research on future mitigation pathways (Vaughan et al. 2018; van Vuuren et al. 2017; Peters 2016; Knutti 2018; Beck & Mahony 2017). Further development of processes in which modelling teams and policy experts systematically negotiate model assumptions that better account for real world constraints to produce what could be called 'purposeful modelling' is a logical next step for scenario input to global climate governance. This would be an example of 'legitimate co-production', where an openly acknowledged and orchestrated mutually constitutive relationship can increase the usefulness of regulatory science by explicitly incorporating socially sanctioned objectives. Such an approach to modelling, which should be viewed as a mutual responsibility for both scientists and policy-makers, can be seen to be emerging in the most recent of publications of IAM scenarios for 1.5 °C pathways (van Vuuren et al. 2018; Rogelj et al. 2018; Grübler et al. 2018; Holz et al. 2018). The challenge now is to incorporate such pathways into global climate governance, in very short time frames.

7.4 Conclusion

The specific aim of this thesis was to examine how land-based mitigation can play a critical role in meeting stringent climate goals, without undermining equity and sustainable development, but rather contributing to the achievement of sustainable development goals. The findings of this thesis are summarized below in three key points.

1. Politics of expert knowledge. With the development of land-use accounting rules, there is a need to recognize that different approaches suit different countries while stimulating a change in anthropogenic terrestrial emissions from a net source to a net sink. Politicization of the science around fungibility (of land / fossil fuel emissions) and carbon neutrality of bioenergy has resulted in overly-complicated land-sector accounting rules that achieve political objectives at the cost of scientific credibility. The Paris Agreement offers an opportunity to focus on robust and transparent reporting of the land sector in all countries – an exercise that can contribute to improved land sector governance in countries where this is critical to maintaining and restoring land carbon stocks.

2. **Limits to terrestrial carbon-dioxide removal.** It is clear from the findings noted earlier that biophysical limits need to inform the supply of land-based negative emissions in IAMs. In this concluding chapter I have suggested that the over-reliance of current IAMs on negative emissions may have caused a 'crisis of expertise', forcing more reflexivity on the part of modellers. Jasanoff (1990) points out that repoliticizing what has been made technical can work as a strategy to 'foreground' risk impacts and vulnerabilities. If there is an over-reliance on land-based sinks for climate mitigation, the impacts will fall largely on rural and resource-dependent communities, where insecure land tenure and low socio-economic status make these groups vulnerable to exploitation and dispossession. Highlighting these impacts in the context of assumptions around land-based negative emissions can serve to repoliticize what was previously a technocratic governance approach based on least cost assumptions.

Previous analysts have argued that perceptions and admissions of uncertainty may vary depending on the end-user (with scientists admitting high levels of uncertainty, while policy makers may admit far lower levels of uncertainty) (Fogel 2005, Keeley & Scoones 2003). Yet my findings point to increasingly explicit attempts on the part of scientists to highlight the uncertainties surrounding the inclusion of land-based negative emissions in IAMs, while policy makers take little notice. Dreyfus and Rabinow (1982) argue that political technologies advance by recasting in the neutral language of science. This seems to be the case with the introduction of negative emissions to models, but as the impacts and (un)feasibility are increasingly understood, a repoliticization of integrated assessment models is underway, illuminating the real-world impacts of model-based assumptions.

3. **Sustainable potential of terrestrial carbon-dioxide removal**. Based on a recognition of the fallibility of technical knowledge, exploiting synergies with sustainable development objectives as an explicitly normative basis to science-for-policy in the context of global climate governance can deliver previously overlooked options for carbon-dioxide removal. The potential in natural ecosystems to contribute to climate mitigation while also contributing to other SDGs such as eliminating poverty and ensuring food security has been overlooked so far in a technocratic approaches to global climate governance. The future will be not only be carbon constrained but also land-constrained. The implications of this for the recognized need for negative emissions to meet the Paris climate goals, while also meeting sustainable development objectives, must be the focus of a self-reflexive approach to co-production of climate science and climate policy that is open, transparent and purposeful.

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Appendix A

Interview questions used in Chapters 4 and 5

Interview questions Chapter 4 – semi-structured

Review Consent statement

There are five broad areas I would like to cover: your role here; your views on land use in a newclimate agreement; your formal and informal network affiliations; any other general views on the topic or what you see as prevalent issues.

About the person's role and organizational affiliation:

What is your role here in the climate negotiations? *(How long has this organization been involved in the land use debate? Area of focus (agriculture, forestry, LULUCF)? What are the main activities in the land–use arena this organization is involved in?)*

History of land use negotiations

We see some clear lessons from LULUCF negotiations – rules before targets, voluntary accounting of activities and ? to name a few. Do you agree with these, do you see other key lessons from the LULUCF discussion?

(What are their views on the LULUCF outcome – do they see these rules as broadly useful or broadly about loopholes).

Architecture of land use in a post-2020 agreement:

Do you think the accounting challenges being dealt with in LULUCF and more recently REDD + are surmountable? Do you think accounting challenges present barriers to the way land use is

included in new agreement? Are special principles needed? What are the main options for ensuring env integrity?

(What is their perspective on a common accounting framework for all vs. a differentiated approach?)

(Does this involve detailed accounting rules? If so, when and how should these be developed?)

How they view equity considerations:

Do you think that the inclusion of the land sector in mitigation implicates equity in terms of how differentiation is dealt with? Why or why not?

(What they see as the key benefits and risks of land sector inclusion. How these risks might be dealt with – through safeguards, design of rules, other? The relative importance of the inclusion of social actors in decision-making vs. leaving technical decision areas to experts.)

Network affiliations:

What formal and informal networks do you associate with? Which other organizations do you strongly collaborate with or strongly disagree with?

(Which organizations do they rely on for scientific advice, if any?)

General views and other issues:

Is there anything we have not covered that you think is an important element of this topic?

Thank participant for their time and ask if they would like to nominate other potential interview candidates.

Interview methodology and questions Chapter 5 – semi-structured

Interview methodology and rationale

In order to answer the research questions, I will look at how science-based mitigation pathways as determined by IAMs have been taken up in the policy context, and to what degree global and national climate strategies under the Paris Agreement differ from or are consistent with IAM 2C pathways. Under the Paris Agreement, all countries are asked to submit a mid-century strategy by 2020. By the end of 2016, four countries had done so: The USA, Mexico, Canada and Germany.

Following an analysis of the latest IAM modelling scenarios for 2C pathways (stage 2 of the methodology – see Chapter outline), I will then conduct interviews with key land-use mitigation policy advisors from each of the four countries who have submitted mid-century strategies; and land-component modellers from each of the 5 key IAM modelling groups.

Interviews will be semi-structured, and last approximately 60 minutes.

Separate questions have been developed for policy advisors and climate modellers, to draw out the relevant points for each group. In addition, specific questions were developed for each modelling group, based on the information provided in background documentation and published literature for each model under study. The interview questions include four clusters of questions that address the science-policy interface in the production and use of IAM models in climate policy, and the sustainability of modelled land-use mitigation options. (Note: for simplification, sustainable land-use will be defined in the methodology section to be concerned with large scale changes in land-use for mitigation, which may impact on food prices and biodiversity).

The research questions are described in the paper outline. The central question I aim to answer through interviews is how/why did BECCS come to occupy the central 'negative emissions' role in the IAMs, as opposed to other land use options for atmospheric carbon removal?

I will also be looking for iterative relationship between policy use/needs and model development, which may illustrate knowledge legitimization and the way science both 'embeds and is embedded in' social practices in an iterative manner (Jasanoff 2004, p. 2).

Presentation of interview results will include a short section for each research question, discussing modellers and policy advisors views over the different questions, and drawing links to other research material (the broader literature, and the findings from analysis of SSP models).

Policy advisors chosen from:[1]

- The four countries which had submitted a long-term climate strategy by the end of 2016.
- Policy (technical) advisors who work in the space between the science / modelling community, and translating and bringing this knowledge into policy processes.

In each of the four countries, I have identified 1 or 2 key people within government who engaged with IAM modelling of land-use in long-term mitigation scenarios, to interview about the science / policy interface in this process.

Modellers chosen from:[2]

Key land-use person in each of the 5 main IAM models in SSP database (see figure 5.?).

Potential modeler 'types'

1. **Techno-optimist:** "2°C and below is an extremely challenging target given the levels of CO2 in the atmosphere and current trends. The scale of annual reductions in emissions that would be required is politically and economically impossible, so the only option left is to remove emissions from the atmosphere. This is a risky option, but development of new

[1] I am denoting policy / technical advisors as those who work within government departments.
[2] I am denoting modellers as those who are directly engaged in modelling processes (not policy processes), and are employed in research institutes.

technologies over the coming decades should make this more achievable (3rd gen bioenergy, other NETS options). The models emphasize that extremely ambitious emissions reductions and efficiency options are needed alongside NETS, but even with the most stringent rate of emissions reductions that are politically and economically feasible, we will still need to remove carbon to limit temperatures to below 2C and 1.5C."

2. **I'm just a modeller:** The models cannot evaluate alternative pathways because they are cost-optimization models. Models choose least-cost options and BECCS significantly lowers the cost of mitigation (discounting and tech costs). Modelling groups are set up for this kind of analysis, incorporating inputs from other disciplines would be too time-consuming – we are working to IPCC and other external cycles, cannot slow down to include different kinds of data / criteria in analysis. Model outcomes can be assessed for sustainability. It's the role of elected officials to make normative choices on the basis of that information that benefits their constituents." Communication and uptake of models is at fault – not the fault of the models. A model is not reality. How can cost of BECCS be known when tech doesn't exist? How is discounting justified?

3. **Unconcerned policy-maker:** we trust the modelling and the answers we get from scientists that these pathways are feasible. The mitigation budget is challenging, but we can do this. Reducing emissions any earlier, or more steeply than what is modelled is not feasible, as it would be too expensive, and would undermine development in poor countries - we need to focus on development for poor people who are suffering today before we prioritize the long-term future problem of climate change. We can meet the Paris Challenge with net-zero.

4. **Science-policy boundaries:** Science needs to be kept separate from policy, to be objective and credible. We fund research projects to get the knowledge we want – that's a bit tricky and need to be careful to let scientists be independent. Policy makers will take the outcomes

of science and make decisions considering the balance of issues. So the key thing for science is to not provide answers that rule out alternative credible options.

Interview questions - modellers

Review Consent statement

Introduction: There are four broad areas I would like to cover: your role; scale of land-use in modelled mitigation scenarios; how social and environmental sustainability of land-based mitigation is considered in these scenarios; and how you see the role of integrated climate models in policy-making.

1. About the person's role and organizational affiliation: (5 mins)

What is your role in the modelling group? What is your background, and how is it relevant to modelling of land-based mitigation? Do you also participate in any policy fora (ie: UNFCCC climate negotiations, others) In what capacity?

2. Land-use in modelled scenarios for RCP2.6 (15 mins)

(focusing on assumptions related to biomass supply, yield increases, land-use change and forest protection and water /nutrient availability).

- Does energy policy or considerations of land use options drive BECCS?
- How transparent do you think IAM models are? Do you consider the input assumptions and outputs for land-use options in models to be readily accessible to policy makers? Why / why not?
- How does uncertainty in LUC projections impact model assumptions? (ie land area availability, yield changes).
- How is feasibility of technologies currently included in models determined – what is the "evidence level" required for incorporation of technology such as BECCS? How is this demonstrated?

3. Sustainability impacts of land-use in modelled pathways (15 mins)

- Were biodiversity and food production specifically considered in developing your land use scenarios? (Through model constraints/parameters)
- How realistic do you think the land based mitigation strategies suggested by your models are? How confident are you in recommending them for use as the basis of policy (e.g, biofuels, plantations).
- Are there alternative mitigation pathways that would avoid NETS, that your models could consider? What options are excluded from mitigation pathways?

4. Policy / science interface (15 mins)

- What kind of contact did you have with policymakers when you were creating the scenarios to run your model? (how much did social goals influence what you chose for your model?)
- How much do you think policy expectations affected what you have modeled and therefore your results?
- To what extent do you see there is a responsibility inherent on the modelling community to understand the sustainability impacts of modelled pathways, or does this responsibility fall to model users?

Interview questions – policy advisors

Review consent statement and overview 4 broad question areas: role; familiarity with and use of modelled mitigation scenarios; views on how sustainability aspects of land-based mitigation are considered; the role of climate models in policy-making.

1. The person's role and organizational affiliation: (5 mins)

2. Familiarity with land-use in modelled scenarios (20 mins)

(focusing on bioenergy supply, land-use change and forest protection assumptions)

5. level of familiarity with the scale of land-use in modelled 2C pathways.

6. Land-use options in mid-century strategy.
7. Feasibility of land-based mitigation options currently included in global models.

3. Sustainability of scale of land-use in modelled pathways vs. mid-century strategy

How do the models account for social / environmental impacts related to land-use mitigation options? To what degree to policy makers pay attention to, and critique sustainability aspects of models?

Food security

8. Land-use regulation used in mid-century strategy
9. Food first policy in global models
10. What level of global food price increase from climate mitigation might be acceptable?

Biodiversity

11. Biodiversity and forest protection achieved in mid-century strategy.
12. How do IAM models address biodiversity, what level of protected areas / REDD+ for forest protection and restoration used in IAM models?

4. Policy / science interface

13. Boundaries between science and policy.
14. How are policy makers best kept informed of relevant science developments?
15. Balance between model-based knowledge and other knowledge.
16. Responsibility for sustainability in models / long-term mitigation pathways

Appendix B

Analysis of submissions to the UNFCCC during 2014 and 2015

Country / country grouping positions – land use in the ADP (based on 2014-2015 country submissions analysis)

Summary:

EU	Legally binding, robust MRV, common rules for all, land-sector rules in accompanying COP decision in Paris (in closed meeting said only principles for land-use agreed by Paris, details later). Carbon stocks should be excluded from accounting. Bottom line is comparability of INDCs
China, LMDC	Targets for developed countries, actions for developing. Reporting under Convention as per Cancun agreements (not common reporting framework), downplays land in new agreement, raised issue of capacity of developing countries to be able to collect large amounts of data on land-use change
EIG	Common accounting for land sector for all Parties
Swiss	'net-zero', quantifiable targets for all parties, common accounting approaches for all parties including in the land sector, provisions for land sector accounting in 2015 agreement
Marshall Islands	Carbon neutrality by mid-century
Norway	Net-zero, common rules for all with flexibility in implementation, unconditional targets and common accounting framework for the land sector (a ton is a ton)
Russia	Land-use and forests should be 'duly accounted for' when setting targets. Targets for developed; measures for developing
South Africa	Zero-carbon pathways for developed (not net-zero). Common accounting for all parties – detailed land use rules should be included in 2015 agreement, wants spin-off group/workshops to develop these in 2015 (so far no workshops planned).
Australia	Reform current 'split-system' of reporting requirements into common system for all. Land-use sector comparable to other sectors.

	Pushed for quantified outcomes in Lima text, wants principles for land sector and markets in Paris agreement
LDCs	1.5C goal, quantified targets for 'parties in a position to do so', qualitative targets for those not in a position, esp. LDCs and SIDs. Role of forests and markets needs further consideration, a lot of complexity here, accounting rules in COP decisions, not in Paris agreement.
Brazil	Don't agree with net-zero target. In general supportive of positions (in our principles paper) except food security threshold as this represents 'a cap on food production emissions – unacceptable', inserted this text in Lima decision – "Methodological approaches and estimations for anthropogenic ghg emissions by sources, and , as appropriate, removals by sinks." In closed meeting said targets will be nationally determined and cannot imply these targets will be automatically translated into units. Carbon stocks should be excluded from accounting.
CfRN	Pledges conditional on support for developing countries, common methodological framework for all, REDD+ critical to 2015 agreement, emphasizing mitigation potential of forests and lands, including wetlands and coastal marine ecosystems
NZ	Net-zero emissions for global goal. Universal MRV framework obliged – optional use of land sector and markets, but must apply common accounting rules if included, COP decision needed on land use accounting – NZ proposal for this in Annex (was discussed by Parties in Lima in closed meeting).
Bolivia	New agreement concerns distribution of remaining global budget. Lima decision pre-judges Paris agreement by establishing a de-facto bottom-up approach with methodologies and everything here in Lima. Identified key issue in Lima text was quantification - and suggested to delete paragraphs 15-22 (Philippines countered with keeping these paras, but adding policies and measures – which did not make it to the final Lima text – only Brazil's language, as above).
US	In closed meeting admitted one size fits all won't work in land sector due to capacity constraints. In general arguing for new Annexes that change country categorization.
Argentina	Including land-use in mitigation puts burden on poverty eradication…this approach is not included in the Convention, as it goes beyond the recognition of transfer of tech. Wants to exclude land use from the new agreement.

	Scope and form of agreement; global goal	Differentiation	Accounting framework	Land-use	Markets	Other comments
EU	Rules based, legally binding, all elements (mitigation centric with adaptation/finance part of agreement).	Variety of commitment types. INDCs for Parties with greater responsibility and capability should be QELROs	robust rules on MRV & accounting as well as compliance provisions are priority information in relation to types of commitments, such as quantified targets, emissions intensity targets, deviation from BAU and PAM	Up front information to include land use approach and effect on emissions/reductions. If including land-use in INDCs, parties must provide info on approach, ref level, etc.	Robust rules for the use of market mechanisms must be finalized in Paris if impacting on level of mitigation effort	COP Decision in Paris on land-use sector to define i the accounting approaches that are acceptable – ie, both activity based and comprehensive accounting as long as rules are transparent and methods based on IPCC Work programme after Paris in order to streamline and improve these accounting approaches for use in future commitment periods.
LMDC	all elements	No deviation from Convention – CBDR is not RC; no ‘	Economy wide for A1 countries; Non A1 have mitigation actions subject to support		Domestic actions: no offsets	At Geneva suggested to delete land from draft text entirely – No land in ADP position
Brazil	Conditional commitments for developing countries. Do not support net-zero	CBDR operationalized through differentiation in INDCs	INDC for all parties to include quantified targets, on a spectrum from economy wide to non-economy wide, and based on base year, projections or emissions-intensity Accounting of highest standards – particularly for offset mechanisms	Developing countries may include REDD+ in INDC with support for results-based actions	Economic mechanism is needed to provide incentives for developing country Parties to consider moving towards economy-wide absolute contributions (CDM+)	Accounting rules must be a top-down element of the Paris agreement – not determined via INDCs

China	all elements. Single or common transparency system does not work	Developed country targets; developing country actions	Differentiation of accounting as per Cancun agreements: Nat comms and BURs for developing countries			Transparency system needs to honor differentiation as established by the convention, as per Art 4 and 12.
AILAC	Legally binding: all elements				Provisions for market and non-market mech in agreement.	REDD+ a priority for mitigation, with modifications for post 2020 agreement
Marshall Islands	Well below 1.5C goal "carbon neutrality" by the middle of the Century – Net-zero	No backsliding for any Parties – QELROs for developed, increase ambition for developing				
EIG	Rules based system applicable to all INDCs for all parties quantifiable	common accounting rules for all; difference in terms of type, stringency, timing according to CBDR/RC and equity.		common accounting framework for the land sector for all Parties		Land-sector principles include: comprehensive reporting and accounting; IPCC guidance; step-wise approach to improving methods; comparability
South Africa	All elements; Global goal -50% below 1990 levels by 2050 - zero-carbon emission pathways	QELROs for developed	Common accounting rules for all parties	For land- or activity-based accounting, rules must be detailed, comprehensive and accurate and simple so developing countries can implement. IPCC guidance	Use of existing mech; New market-based mechanism; Supplementary threshold of 10% for international offsets	Accounting rules should be included in the 2015 agreement. Detailed guidelines for accounting of land use change and forestry under the Convention needs to be developed – suggest a spin-off group on LULUCF

Australia	All elements with complementary decisions. minimum commitment is not conditional on support - additional commitments may be conditional.	reforming current system of split reporting guidelines and review processes into a single set of guidelines and processes	Quantifiable emissions reduction commitments by all. Common MRV system for all to apply from 2020.	Rules for land sector accounting that treat the land sector comparably to other sectors;		Principles for land sector: incentivize real abatement; recognize emissions and removals; and exclude non-anthropogenic emissions;
Russia	Legally binding regime,	Dynamic differentiation based on scientific information.	Commitments for developed countries and measures for developing ones.	Land-use and forests should be duly accounted for when setting targets.	use of markets can increase effectiveness	
Japan	Mitigation centric INDCs	Dynamic interpretation of CBDR.	QELROs for major economies	Main gases or sectors accounting for the majority of total anthropogenic GHG emissions should be put forward with its NDC.	market mechanisms, including how to avoid double counting, should be developed internationally.	The accounting rules on the land sector should be flexible and inclusive enough to give incentives for actions of each Party and to be able to reflect national circumstances – take note of discussions on more comprehensive accounting under KP
Switzerland		quantifiable unconditional commitments for all Parties	Common accounting approach for all parties, including in the land sector Reporting under the 2015 Agreement should build on the experiences from the current reporting arrangements (BR, BURs and IAR)	Cover all sectors and gasses causing high GHG emissions 2015 Agreement to include provisions to report on emissions and removals		
Norway	Unconditional targets	all Parties to limit and reduce	common multi-lateral rules,	Ton CO2e best way to measure mitigation –	enhance collective action through the	Common framework for all for land sector accounting

		emissions, differentiation in flexibility for implementation (based on difference, not fixed categories)	QELROs for major economies (based on current emission levels)	including land use emissions and removals Land-use included in INDC	use of national, regional and international carbon markets in 2015 agreement	
LDCs	1.5C goal	QELROs for 'parties in a position to do so', a range of targets for others *(not convention language, opposed by LMDC)*	developing country Parties might propose both result-based commitments and activity-based commitments (qualitative targets)	QELROs include land sector emissions	COP will consider at a later date international linking of national ETS (not for 2015)	Role of forests and markets needs further consideration All parties address drivers to DD – existing REDD modalities apply to new agreement (do no harm IP rights safeguard expressed).
US	Some part of pledges must be unconditional	CBDR/RC), differentiated across a broad continuum of Parties, but cannot support a bifurcated approach	Quantified targets except for countries with limited capacity/low emissions Single system for reporting post 2020 - accounting should apply to all Parties, including land use accounting (same approach in base and target years)	INDCs may include more than one mitigation contribution, ie a hard cap in one sector with emissions that are easy to project, an intensity target in another sector, and policies in a third sector.	Voluntary use of market mechanisms	Mitigation efforts in the land sector, including REDD+, are important, if included in INDCs must specify how the Party will account for all significant lands, activities, pools, and gases
Sudan (Africa Group)	Well below1.5C goal	Differentiated approach to developed and developing country commitments in	recall agreement on reporting systems already agreed under the Convention, including nat comms BURs, IAR and ICA	Difference between counting and accounting (LULUCF rules in accounting)		Building on the agreed outcome, and existing mechanisms under the Convention, agree on market and non-market mechanisms, LULUCF rules, implementation

		line with Convention principles				of REDD+,
CfRN	Well below 1.5C goal	Differentiation for LDCs and SIDs. Conditional pledges from developing countries	Common methodological framework in 2015 agreement	conservation of sinks and reservoirs should be promoted. REDD+ should be fully integrated in the 2015 agreement as one of its key elements	Market and non-market approaches for REDD+	consider a framework for incentivizing mitigation actions of wetlands and coastal marine systems. Consider broader AFOLU sector contribution to climate change mitigation as of 2020 (start discussion in 2016)
New Zealand		No binary differentiation – dynamic implementation of CBDR-RC Does not want to divert resources to quantification of finance/support	Universal MRV framework **obliged** Accounting rules needed – particularly for land and markets Quantified INDCs, based on agreed methodologies for land sector, if included.	optional right to use **net land sector removals** to help meet mitigation - a Party opting to include the land sector would be expected to apply agreed accounting methodologies	optional right to use carbon markets Paris COP decision on rules for use of carbon markets (FVA)	Paris COP decision needed on accounting principles for the land sector, including expert reviews and reference levels – 2 page annex in Oct 2014 submission on land sector accounting rules Suggests text in agreement on need to accommodate multiple uses of land, including food production

Appendix C

Data and calculations supporting Chapter 5

Available online: https://www.cambridge.org/core/journals/global-sustainability/article/coproducing-climate-policy-and-negative-emissions-tradeoffs-for-sustainable-landuse/CE06F8A4BB2745389C53EEBE84EB95E7#fndtn-supplementary-materials

Data source:

© SSP Public Database (Version 1.1) https://tntcat.iiasa.ac.at/SspDb
generated: 2018-01-18 11:47:14

Calculations for Figure 5.1

Appears in Figure 5.1 as:	Value	Scenario	Model	2050	2100
black shapes (circle, triangle, etc)	Primary energy, biomass	SSP2, RCP26	AIM/CGE	103.792	212.791
			GCAM4	165.454	391.743
			IMAGE	145.629	180.756
			MESSAGE-GLOBIOM	87.284	206.106
			REMIND-MAGPIE	119.169	323.400
	Primary energy, biomass w/ CCS	SSP2, RCP26	AIM/CGE	45.551	164.494
			GCAM4	57.057	230.255
			IMAGE	40.355	82.621
			MESSAGE-GLOBIOM	11.371	157.560
			REMIND-MAGPIE	95.650	293.000
min = bottom of grey bar, median = grey line, max = top of grey bar	Primary energy, biomass	All SSPs, RCP26	min	61.587	77.929
			median	119.169	226.074
			max	204.320	477.000
min = bottom of red bar, median = red line, max = top of red bar	Primary energy, biomass w/ CCS	All SSPs, RCP26	min	5.479	47.065
			median	45.551	164.494
			max	159.600	417.200

15 model runs referred to in text, those below 100 EJ/year primary bioenergy demand in red:

Model	Scenario	SSP	RCP	Region	Variable	Unit	2010	2050	2100
AIM/CGE	SSP1-26	SSP1	26	World	Primary Energy|Biomass	EJ/yr	44.94	62.85	77.93
AIM/CGE	SSP2-26	SSP2	26	World	Primary Energy|Biomass	EJ/yr	46.55	103.79	212.79
AIM/CGE	SSP4-26	SSP4	26	World	Primary Energy|Biomass	EJ/yr	49.25	119.17	192.45
AIM/CGE	SSP5-26	SSP5	26	World	Primary Energy|Biomass	EJ/yr	45.04	204.32	437.07
GCAM4	SSP1-26	SSP1	26	World	Primary Energy|Biomass	EJ/yr	51.53	93.47	210.94
GCAM4	SSP2-26	SSP2	26	World	Primary Energy|Biomass	EJ/yr	51.53	165.45	391.74
GCAM4	SSP4-26	SSP4	26	World	Primary Energy|Biomass	EJ/yr	51.53	176.78	448.15
GCAM4	SSP5-26	SSP5	26	World	Primary Energy|Biomass	EJ/yr	51.53	170.31	373.30
IMAGE	SSP1-26	SSP1	26	World	Primary Energy|Biomass	EJ/yr	52.84	84.70	226.07
IMAGE	SSP2-26	SSP2	26	World	Primary Energy|Biomass	EJ/yr	52.10	145.63	180.76
MESSAGE-GLOBIOM	SSP1-26	SSP1	26	World	Primary Energy|Biomass	EJ/yr	54.82	61.59	190.55
MESSAGE-GLOBIOM	SSP2-26	SSP2	26	World	Primary Energy|Biomass	EJ/yr	54.99	87.28	206.11
REMIND-MAGPIE	SSP1-26	SSP1	26	World	Primary Energy|Biomass	EJ/yr	59.90	86.75	227.50

REMIND-MAGPIE	SSP2-26	SSP2	26	World	Primary Energy|Biomass	EJ/yr	59.41	127.80	323.40
REMIND-MAGPIE	SSP5-26	SSP5	26	World	Primary Energy|Biomass	EJ/yr	59.83	178.40	477.00

Calculations for Figure 5.2

Model	SSP	Variable	RCP26 2010	Baseline 2100	RCP26 2100	Energy crops proxy	RCP26 2100-RCP26 2010	RCP26 2100-RCP 2010 Min	RCP26 2100 - RCP 2010 Median	RCP26 2100 - RCP 2010 Max
AIM/CGE	SSP1	Land Cover|Cropland	1549.11		1303.0483		-246.0617			
GCAM4	SSP1	Land Cover|Cropland	1502.29959		1344.90734		-157.3922504	These values are the lower, median, and upper graphed in the bars in Fig 2		
IMAGE	SSP1	Land Cover|Cropland	1582.7197		1646.4267		63.707			
MESSAGE-GLOBIOM	SSP1	Land Cover|Cropland	1546.159		1860.46259		314.303586			
REMIND-MAGPIE	SSP1	Land Cover|Cropland	1525.1056		1849.8549		324.7493			
AIM/CGE	SSP2	Land Cover|Cropland	1556.3247		1799.3746		243.0499			
GCAM4	SSP2	Land Cover|Cropland	1502.29959		2190.15123		687.8516427			
IMAGE	SSP2	Land Cover|Cropland	1589.8543		1900.947		311.0927	green values are graphed as points in Fig 2		

MESSAGE-GLOBIOM	SSP2	Land Cover|Cropland	1546.159	2042.00533	495.8463271			
REMIND-MAGPIE	SSP2	Land Cover|Cropland	1518.0651	2273.9697	755.9046			
AIM/CGE	SSP4	Land Cover|Cropland	1558.973	1728.7996	169.8266			
GCAM4	SSP4	Land Cover|Cropland	1502.29959	2935.73018	1433.430591			
AIM/CGE	SSP5	Land Cover|Cropland	1549.4773	2132.8371	583.3598			
GCAM4	SSP5	Land Cover|Cropland	1502.29959	1625.05415	122.7545645			
REMIND-MAGPIE	SSP5	Land Cover|Cropland	1518.4997	2387.3233	868.8236	-246.0617	314.303586	1433.43059
AIM/CGE	SSP1	Land Cover|Forest	3885.8412	4862.7839	976.9427			
GCAM4	SSP1	Land Cover|Forest	4090.35702	5140.70805	1050.351031			
IMAGE	SSP1	Land Cover|Forest	3705.642	4277.3544	571.7124			
MESSAGE-GLOBIOM	SSP1	Land Cover|Forest	3893.26837	4553.7828	660.5144266			
REMIND-MAGPIE	SSP1	Land Cover|Forest	4149.2401	4143.2399	-6.0002			
AIM/CGE	SSP2	Land Cover|Forest	3873.4348	4462.7137	589.2789			
GCAM4	SSP2	Land Cover|Forest	4090.35702	4654.33453	563.9775116			

IMAGE	SSP2	Land Cover|Forest	3704.2796	3873.07	168.7904			
MESSAGE-GLOBIOM	SSP2	Land Cover|Forest	3893.26837	4479.12803	585.859657			
REMIND-MAGPIE	SSP2	Land Cover|Forest	4174.6518	4082.3681	-92.2837			
AIM/CGE	SSP4	Land Cover|Forest	3872.6569	4285.1427	412.4858			
GCAM4	SSP4	Land Cover|Forest	4090.35702	3923.13369	-167.2233312			
AIM/CGE	SSP5	Land Cover|Forest	3878.0279	4268.5418	390.5139			
GCAM4	SSP5	Land Cover|Forest	4090.35702	5017.79024	927.4332141			
REMIND-MAGPIE	SSP5	Land Cover|Forest	4154.5514	4146.8023	-7.7491	-167.22333	563.977512	1050.35103
AIM/CGE	SSP1	Land Cover|Other Natural Land	4447.9767	4198.3401	-249.6366			
GCAM4	SSP1	Land Cover|Other Natural Land	3786.01296	3437.8986	-348.114354			
IMAGE	SSP1	Land Cover|Other Natural Land	4427.9681	4541.2937	113.3256			
MESSAGE-GLOBIOM	SSP1	Land Cover|Other Natural Land	3619.74936	3637.79945	18.05009863			
REMIND-MAGPIE	SSP1	Land Cover|Other Natural Land	4004.6021	4110.7109	106.1088			
AIM/CGE	SSP2	Land Cover|Other Natural Land	4413.5094	3697.8881	-715.6213			

GCAM4	SSP2	Land Cover|Other Natural Land	3786.0 1296	3261. 27287	-524.7400842			
IMAGE	SSP2	Land Cover|Other Natural Land	4420.1 794	3923. 7578	-496.4216			
MESSAGE-GLOBIOM	SSP2	Land Cover|Other Natural Land	3619.7 4936	3342. 35081	-277.3985495			
REMIND-MAGPIE	SSP2	Land Cover|Other Natural Land	3999.6 521	4051. 3592	51.7071			
AIM/CGE	SSP4	Land Cover|Other Natural Land	4419.9 1	3953. 7115	-466.1985			
GCAM4	SSP4	Land Cover|Other Natural Land	3786.0 1296	2768. 04241	-1017.970544			
AIM/CGE	SSP5	Land Cover|Other Natural Land	4416.0 046	3578. 7902	-837.2144			
GCAM4	SSP5	Land Cover|Other Natural Land	3786.0 1296	3360. 18585	-425.82711			
REMIND-MAGPIE	SSP5	Land Cover|Other Natural Land	4016.8 607	4064. 4082	47.5475	-1017.9705	-348.11435	113.3256
AIM/CGE	SSP1	Land Cover|Pasture	3360.2 658	2879. 0214	-481.2444			
GCAM4	SSP1	Land Cover|Pasture	3253.4 8282	2705. 80495	-547.6778671			
IMAGE	SSP1	Land Cover|Pasture	3184.7 666	2383. 0926	-801.674			
MESSAGE-GLOBIOM	SSP1	Land Cover|Pasture	3417.4 1061	2424. 54249	-992.8681112			

REMIND-MAGPIE	SSP1	Land Cover|Pasture	3095.6157		2670.7577		-424.858		
AIM/CGE	SSP2	Land Cover|Pasture	3399.9248		3283.2174		-116.7074		
GCAM4	SSP2	Land Cover|Pasture	3253.48282		2523.45634		-729.9194262		
IMAGE	SSP2	Land Cover|Pasture	3186.795		3146.1208		-40.6742		
MESSAGE-GLOBIOM	SSP2	Land Cover|Pasture	3417.41061		2613.410317		-804.3074346		
REMIND-MAGPIE	SSP2	Land Cover|Pasture	3082.1945		2366.48664		-715.3281		
AIM/CGE	SSP4	Land Cover|Pasture	3391.6538		3275.54		-116.1138		
GCAM4	SSP4	Land Cover|Pasture	3253.48221		3002.441002		-251.0721839		
AIM/CGE	SSP5	Land Cover|Pasture	3399.6839		3263.0246		-136.6593		
GCAM4	SSP5	Land Cover|Pasture	3253.48282		2626.428616		-627.1966575		
REMIND-MAGPIE	SSP5	Land Cover|Pasture	3084.6517		2176.0297		-908.622	-992.86811	-547.67787	-40.6742
AIM/CGE	SSP1	Land Cover|Cropland to calculate energy proxy	1303.0483		1598.16053	-295.557			
GCAM4	SSP1	Land Cover|Cropland to calculate energy proxy	1344.90734		1338.14906	6.4167321			
IMAGE	SSP1	Land Cover|Cropland to calculate energy proxy	1646.4267		1546.1321	100.2946			
MESSAGE-GLOBIOM	SSP1	Land Cover|Cropland to calculate energy proxy	1860.46259		1697.455193	162.910658			
REMIND-MAGPIE	SSP1	Land Cover|Cropland to calculate energy proxy	1849.8549		1090.15275	759.3274			
AIM/CGE	SSP2	Land Cover|Cropland to calculate energy proxy	1799.3746		1948.12633	-148.8887			
GCAM4	SSP2	Land Cover|Cropland to calculate energy proxy	2190.15123		1826.732542	363.825804			

IMAGE	SSP2	Land Cover|Cropland to calculate energy proxy	1900.947	1818.7644	82.1826				
MESSAGE-GLOBIOM	SSP2	Land Cover|Cropland to calculate energy proxy	2042.0533	1940.40007	101.605255				
REMIND-MAGPIE	SSP2	Land Cover|Cropland to calculate energy proxy	2273.9697	1817.9954	455.9743				
AIM/CGE	SSP4	Land Cover|Cropland to calculate energy proxy	1728.7996	2008.0016	-279.202				
GCAM4	SSP4	Land Cover|Cropland to calculate energy proxy	2935.73018	1761.32795	1174.40223				
AIM/CGE	SSP5	Land Cover|Cropland to calculate energy proxy	2132.8371	1845.5267	287.3104				
GCAM4	SSP5	Land Cover|Cropland to calculate energy proxy	1625.05415	1419.43738	205.616769				
REMIND-MAGPIE	SSP5	Land Cover|Cropland to calculate energy proxy	2387.3233	1792.317	595.0063		-295.557	162.910658	1174.40223