Missing Paths to Justice

The Knowledge Politics of Carbon Dioxide Removal

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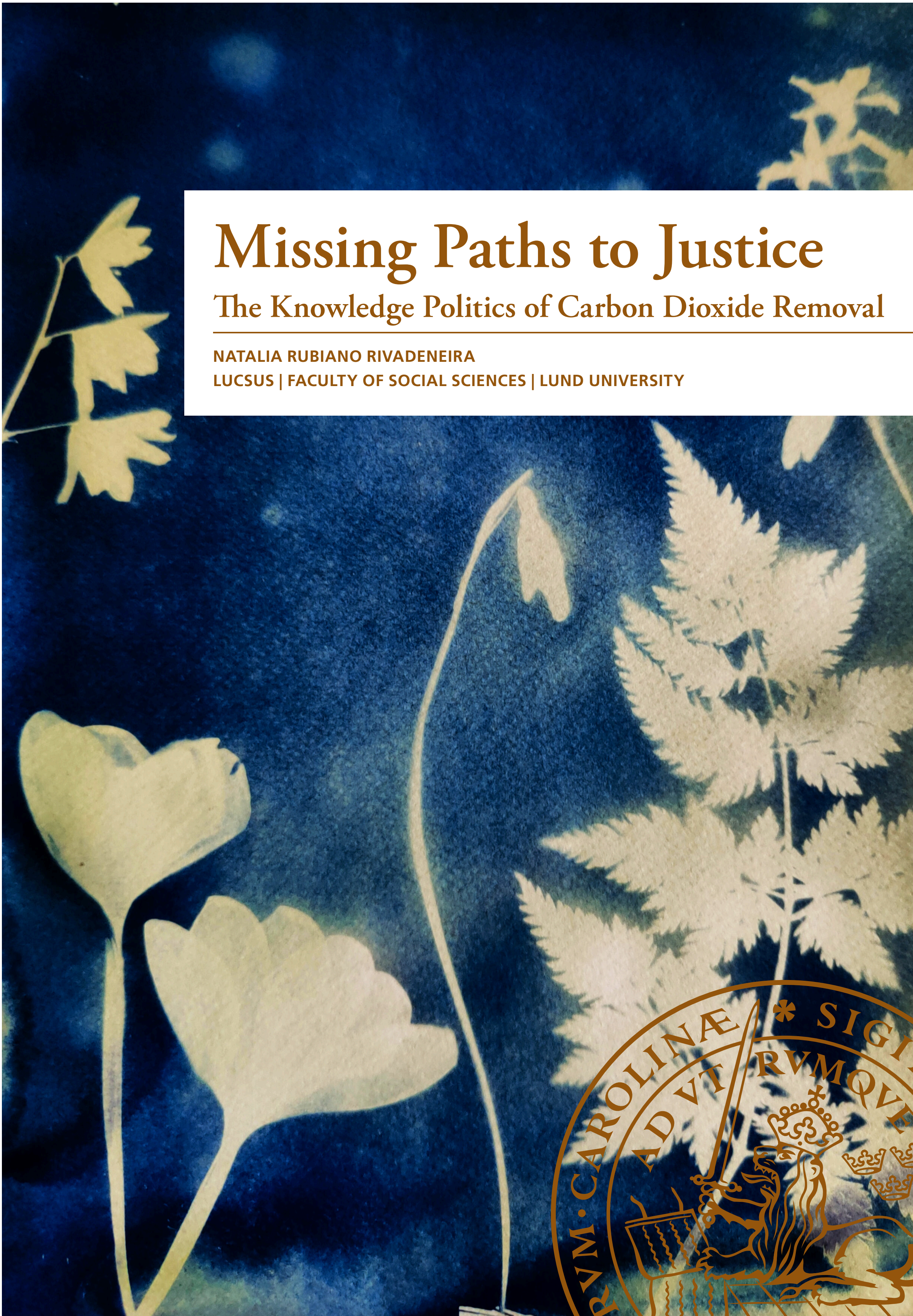

Missing Paths to Justice

The Knowledge Politics of Carbon Dioxide Removal

NATALIA RUBIANO RIVADENEIRA
LUCSUS | FACULTY OF SOCIAL SCIENCES | LUND UNIVERSITY

Missing Paths to Justice

This thesis offers a critical examination of the production of 'policy-relevant' knowledge and its effects in the context of climate change mitigation scenarios produced with Integrated Assessment Models. It traces the translation of model-based scenarios into the real world and scrutinizes Carbon Dioxide Removal (CDR) as the most recent manifestation of the politics of knowledge in climate change mitigation research, shedding light on the potential socio-ecological, political, and material impacts of large-scale CDR deployment. By revealing the often-overlooked injustices inherent in current and model-based future mitigation strategies, this thesis challenges us to rethink our approach to climate change mitigation, emphasizing the imperative of recognizing and addressing power dynamics, material realities, and justice concerns in order to shape a fight against climate change towards a future that is just and equitable.

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The Knowledge Politics of Carbon Dioxide Removal

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LUND UNIVERSITY

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Abstract:

Carbon dioxide removal (CDR) has become a central component in the climate change mitigation scenarios assessed by the IPCC. These scenarios rely on the large-scale deployment of Bioenergy with Carbon Capture and Storage (BECCS) and Afforestation to keep global average temperatures below 2°C of warming, despite substantial concerns about their feasibility, scalability, and unwanted impacts.

In this thesis, I provide a critical examination of policy-relevant knowledge production and its effects, by scrutinizing CDR as the most recent manifestation of the politics of knowledge in climate change mitigation research. I do this through an in-depth analysis of some of the core assumptions in the production of mitigation pathways through Integrated Assessment Models (IAMs) and their socio-ecological, political, and material effects on the ground. In the analytical approach of this study, I integrate insights from Science and Technology Studies, Political Ecology, and Justice debates. Specifically, I draw upon debates on knowledge co-production to investigate the emergence, mobilization, and transformation of visions of carbon removal and the ways in which they influence action in the present. From a justice perspective, I pay particular attention to some of the Global North – Global South dynamics and materialities assumed in this science-for-policy space and the visions of the future it generates.

First, drawing on a literature review I analyse the ways in which justice concerns are subsumed or disregarded in the integrated assessment modelling of climate change. This justice angle allows me to make the politics of knowledge in climate change mitigation models visible, and to contextualize the emergence of CDR in mitigation scenarios and pathways. Based on findings from this review, I empirically explore how emerging visions of the future in global modelled scenarios and pathways get translated and negotiated into actionable imaginaries and policies which in turn have effects on the ground. I do this by examining the effects of these visions for two components of BECCS: land use change and carbon capture and storage.

My findings show that model-based policy-relevant research often overlooks the power dynamics and materialities embedded in both the practical process and underlying assumptions of knowledge production. This oversight can result in fundamentally unjust outcomes and policy recommendations. My results underscore the imperative to first, recognize the political nature of doing research for policy and second, to explore alternative ways of imagining more just and equitable futures.

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Abstract

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List of Papers

Paper I

Rubiano Rivadeneira N. and Carton W. (2022) (In)justice in modelled climate futures: A review of integrated assessment modelling critiques through a justice lens. Energy Research and Social Science. https://doi.org/10.1016/j.erss.2022.102781

Paper II

Rubiano Rivadeneira N. (2023) Imagining large-scale carbon removal in tropical savannas: Lessons from land-use change in the Brazilian Cerrado (Manuscript under review).

Paper III

Lefstad L. and Rubiano Rivadeneira N. (2023) From the rainforest to the Fjords: From the Rainforest to the Fjords: Equity in carbon capture and storage policy (Manuscript under review).

Author’s contribution to the papers

Paper I

NR developed the idea with support from WC. NR undertook data collection, analysis and writing with input from WC. Both authors refined and revised the manuscript.

Paper II

NR conceptualized the paper, collected, and analysed the data, wrote, and revised the manuscript.

Paper III

NR and LL contributed equally to the design, data collection, analysis, and writing of the manuscript.

Abbreviations

A/R	Afforestation / Reforestation
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
BECCS	Bioenergy with Carbon Capture and Storage
CBDR	Common but differentiated responsibilities
CCS	Carbon Capture and Storage
CDR	Carbon dioxide removal
COP	Conference of the Parties
GHG	Greenhouse gases
$GtCO_2$	Gigatons of CO_2
IAMs	Integrated Assessment Models
IPCC	Intergovernmental Panel for Climate Change
NETs	Negative Emissions Technologies
NDCs	Nationally Determined Contributions
PA	Paris Agreement
RCPs	Representative Concentration Pathways
STI	Sociotechnical Imaginaries
SR1.5	Special report on the impacts of global warming of 1.5 °C
SSPs	Shared Socio-Economic Pathways
STS	Science and Technology Studies
UNFCCC	United Nations Framework Convention on Climate Change
WGIII	Working Group III

Introduction

In 2015, the 195 United Nations Member States committed to limiting "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". During the 21st UNFCCC Conference of the Parties (COP21) that produced the now well-known 'Paris Agreement', the IPCC was also invited to produce a Special Report exploring the impacts of global warming of 1.5 °C above pre-industrial levels and related global emission pathways. Already back in 2007, in its Fourth Assessment Report (AR4), the IPCC stated that to stay within 2 °C of warming emissions needed to peak by 2015, i.e. the year the Paris Agreement was signed. Exploring pathways to restrict warming to 1.5°C therefore posed a substantial challenge for the scientific community tasked with this effort.

Although Carbon Dioxide Removal (CDR) was already considered in some pathways and scenarios from AR5, the Special Report, completed in 2018, illustrated just how deep the dependence on CDR had become. In it, "all pathways that limit global warming to 1.5°C with limited or no overshoot projected the deployment of carbon dioxide removal (CDR) at a scale of 100–1000 GtCO2 over the 21st century" (IPCC, 2018). In the models that underpinned such assessments, large-scale CDR extended the carbon budget and then compensated for that extension with overall 'negative' emissions in the second half of the century. Such negative emissions were mostly achieved – still in the models – through the large-scale deployment of Bioenergy with Carbon Capture and Storage (BECCS) and Afforestation/Reforestation (A/R). Both are land-intensive methods requiring – in some instances – land equivalent to two and a half times the size of India, or almost half of the world's arable land (Smith et al., 2016). And, in the case of BECCS, the large-scale deployment of Carbon Capture and Storage (CCS), an expensive and largely unproven technology (Geden, 2015).

The inclusion of CDR at an unprecedented scale in modelled scenarios elicited concerns from numerous scholars (Anderson and Peters, 2016; Fuss et al., 2014; Smith et al., 2016; Williamson, 2016) and bolstered critical analyses around the use and assumptions of modelled scenarios (Gambhir et al., 2019; Geden, 2015; Pindyck, 2017; Robertson, 2020; Rosen, 2021). It also reinvigorated questions about the role of the IPCC in shaping future mitigation action (Beck and Mahony, 2018a; Beck and Oomen, 2021), and the role of politics in shaping science (Anderson, 2015; Hulme, 2016).

These debates and controversies underscore the challenges of integrating scientific insights into policymaking and formulating future-oriented climate strategies. In climate change and environmental policy in general, science plays a crucial role in providing evidence that allows informed decision-making. Scientific research alone cannot provide definitive answers to policy questions; it also does not aim to do so. Yet, when science is tasked with exploring answers to questions of policy, the boundaries between scientific inquiry and political decision-making often get blurred (Jasanoff, 1990; Miller, 2001).

Social scientists have long been interested in what happens at this boundary. Research on the Politics of knowledge for instance examines the ways in which scientific knowledge influences decision-making but also how political interests in turn shape scientific research (Jasanoff, 2004; Livingston and Rummukainen, 2020; Lövbrand, 2011; Turnhout, 2018), in other words, how science and society co-produce each other. This field departs from the notion that acts of knowledge production are inextricably linked to specific social, material, cultural, and political contexts (Jasanoff, 2004; Latour, 1993). Scientific knowledge therefore necessarily reflects the values inherent in the societal contexts where it originates; knowledge is inherently situated (Haraway, 1988). This in turn means that the way certain knowledge is generated and applied stabilizes specific understandings of the world (Hulme, 2010). The climate research that this thesis focuses on is grounded on techno-economic framings and originates from large datasets and complex models. For this reason, it is often presented as value neutral. This framing, however, tends to underestimate the political nature of efforts to produce policy-relevant knowledge without recognition of the contexts in which such efforts take place. It also overlooks the specific power dynamics and materialities embedded in knowledge production and its underlying assumptions, as I will show in this thesis.

The emergence and subsequent dominance of large-scale CDR in IPCC scenarios was in large part a function of what was considered techno-economically feasible in algorithmic models, rather than of a comprehensive assessment integrating economic with socio-ecological and political dimensions (Fuss et al., 2014). As a result, scholars raised concerns about the real-world feasibility, scalability and sustainability of CDR (Anderson and Peters, 2016; Carton, 2019; Williamson, 2016). Numerous studies have outlined a series of potential negative effects expectable from the deployment of, in particular, land-intensive removal methods, especially when prioritized instead of other societal priorities such as food security, biodiversity conservation, acknowledgement of land rights and water availability (Creutzig, 2016; Dooley et al., 2018; Dooley and Kartha, 2018; Heck et al., 2016; Smith et al., 2016).

Nevertheless, despite the excessive optimism in light of profound uncertainty regarding the feasibility of CDR deployment, scenario-based assessments have contributed to shaping extensive commitments towards CDR in national climate plans and policies, with CDR currently featuring in 121 out of 167 Nationally

Determined Contributions (NDCs) under the Paris Agreement (Fyson and Jeffery, 2019). The vast majority takes the form of land-based methods, mainly afforestation. According to the Global Land Gap Report, fulfilling governments' pledges for these methods would demand 1.2 billion hectares of land, an area roughly equivalent to the current global cropland area (Dooley et al., 2022). Therefore, with the feasibility and merit of CDR in question, it is pivotal to understand the role played by computational models and their underlying assumptions in forecasting large-scale CDR as a plausible and cost-effective climate change mitigation method, especially in the context of policy-relevant research and the IPCC.

The models used for this type of policy-relevant research are called Integrated Assessment Models, or IAMs. They combine socio-economic, technological and biogeochemical variables to explore the effects of different climate policies, and aim to provide quantitative policy-relevant insights for decision-making (Weyant, 2017). IAMs use extensive datasets, intricate software codes, and powerful computing capabilities to present a simplified techno-economic view of the world, granting them cultural authority and creating an appearance of objectivity, universality and value-neutrality (Hulme, 2013). Consequently, the solutions that stem from the ‘mitigation pathways’ that these models produce are often presented as globally coordinated, cost-efficient and value-neutral options, detached from historical political, socio-ecological and material contexts. This ‘technicalization’ of knowledge denies its own political character and can contribute to reinforcing inequities and uneven power dynamics.

For instance, scholars have observed how modelled scenarios tend to reflect the values and preferences of modellers (Ellenbeck and Lilliestam, 2019), or perpetuate prevailing societal discourses (Beck and Krueger, 2016). By outlining what is technically possible within a limited range of modelled futures, IAMs tend to support and promote specific political agendas and power structures (Beck and Mahony, 2018a; Beck and Oomen, 2021). Moreover, the emphasis on cost optimization inherent in them, coupled with a narrow perspective on the kind of futures that are possible (Beck and Mahony, 2018), may tacitly contribute to the perpetuation of unjust structures and lead to inequitable outcomes, with regard to e.g. land rights, food security, biodiversity conservation and other competing land uses (Deprez et al., 2024; Dooley and Kartha, 2018; Heck et al., 2018; McElwee, 2022).

Equity and climate justice have become central mobilizing claims in international negotiations and climate activism. Equity is a foundational principle in the UNFCCC and the Paris Agreement. Yet in science-for-policy spaces, these concerns has so far been sidelined or explicitly avoided. Therefore, as calls for climate justice continue to grow, justice considerations warrant more attention in policy-relevant climate knowledge production. Examining the controversies and scientific practices surrounding CDR through the lenses of justice, co-production, and performativity provide one way to do so. This helps us understand and elucidate who gets to speak for the future, or as Lövbrand et al. put it, "whose nature is being represented and what the material effects of such representations are" (Lövbrand et al., 2015, p. 231).

In this thesis, I use the case of CDR to provide an in-depth examination of policy-relevant knowledge production and its effects from a justice perspective. A central focus of my work is an analysis of how conceptions of CDR emerge (Paper I), are mobilized, and become forces of action in the present (Paper II and III). Together, this helps me investigate both the performative role and the potential real-world implications of carbon dioxide removal technologies as envisioned in modelled mitigation scenarios.

The thesis also aspires to go beyond a purely global perspective. So far there has been very little focus on the localized dimensions of CDR visions, and yet that is ultimately the scale at which these debates and controversies matter. For instance, a critical aspect that needs consideration is the envisioned large-scale deployment of land-based Carbon Dioxide Removal in the Global South and the scale of its projected mitigation potential. Essentially all these projections are driven by model parameter choices, assumptions about land availability, technological scalability, and effectiveness of implementation, all estimated with – at best – high uncertainty and – at times – profound optimism or a certain level of arbitration. Therefore, the factual merit of CDR may fall well behind optimistic model assumptions in the real world and yet come with justice implications that warrant closer examination. A largely underexamined aspect of this are the impacts on land rights and land tenure (Bluwstein and Cavanagh, 2023; McElwee, 2022).

Uncovering the politics and hidden biases in the production and circulation of knowledge is a first step towards creating spaces for more equitable futures (Dooley et al., 2021; Forsyth, 2014; Kanbur and Shue, 2019; Klinsky et al., 2017) and alternative forms of knowledge (Sultana, 2021). The kind of deep, justice-focused scrutiny of contemporary climate mitigation research that this thesis provides is necessary to help unpack the uneven materialities and power dynamics in our understandings of climate change and provides foundations for a just exploration of what different understandings of and responses to climate change might look like.

Aim and Research Questions

The overarching aim of this thesis is to examine the politics of knowledge of CDR and its effects on climate governance, policy, and justice. This aim has two central goals: first, to render the politics of knowledge in models visible by contextualizing them in relation to justice and Global North-South dynamics; and second, to examine the potential local and practical implications of such global visions of CDR through empirical cases.

To accomplish this, I pose the following three research questions:

1. How do justice concerns manifest in global policy-relevant climate change mitigation scenarios?
2. What socio-ecological, material, and political dynamics might large-scale CDR deployment, as depicted in models, contribute to perpetuate, challenge, or obscure?
3. How do global scenarios with CDR translate into national climate policy and action?

Thesis outline

I present my results in the form of this Kappa (Swedish for “cover” or “coat”) section and three scientific papers. Each paper primarily addresses one research question.

The purpose of this Kappa is to both synthesize and complement the arguments presented in the three papers. Its main goal is to show how the papers address the overall aim and research questions of the thesis in a cohesive storyline. Additionally, it provides more detailed insights into some arguments that could not be fully explored in the papers. This Kappa is structured into 7 chapters.

In the next chapter, I provide a detailed overview of the origin and role of climate change mitigation scenarios, some of their main critiques and the inclusion of CDR in modelling efforts. Second, I describe in depth the theoretical framework employed to contextualize the findings, followed by a granular explanation of the research design and methods employed to perform this study. Then, I present the main findings of my research, and lastly, I offer an integrated discussion reflecting on the key contributions and contextualize them within broader scholarly debates.

Context

In this chapter, I provide a brief overview of the history and co-productionist role of models and mitigation scenarios within the IPCC and climate policy. I then summarize some of the main concerns and critiques raised in the scholarly literature about the assumptions and uses of these models. Afterwards, I place them in the context of the emerging idea of Carbon Dioxide Removal.

Modelling Climate Futures

A brief history of Integrated Assessment Modelling for Climate Change

Models have been an essential tool to shape our current understanding of climate change. They were the key to recognising the link between CO_2 and the atmosphere in the 1800s and have been essential to the increasing understanding of the impacts of anthropogenic CO_2 emissions in the climate since over half a century ago. As historian Paul Edwards writes: “Everything that we know about the world’s climate—past, present, and future—we know through models” (Edwards, 2010). The epistemic authority of models in understanding the physical dimensions of climate change also enabled them to become the main tools for studying the future dimensions of a changing climate, exploring solutions to the problem, and informing long-term decision-making (Hulme, 2013).

A diverse array of numerical models is employed in climate change research, each fulfilling different roles. At the global scale, General Circulation Models (GCMs) are used to simulate the climate system. Earth System Models (ESMs) incorporate a representation of the carbon cycle and several other components, like vegetation, ice sheet or land surface interactions to provide a more comprehensive representation of the Earth System. Integrated Assessment Models (IAMs) ‘integrate’ biophysical and economic aspects to simulate broader climate-society interactions (IPCC, 2018a). Through this integration, IAMs serve as tools to access the distant future by simulating the impacts of climate change and different development pathways and policy scenarios. Climate Models are foundational to the IPCC's knowledge claims and risk assessments, shaping expert judgment and influencing political narratives (Hulme, 2013), and IAMs are the backbone of The IPCC's Working Group III, which deals with climate change mitigation.

IAMs for climate change began in the 1980s, as a way to study the impacts of climate change on the economy (Yang et al., 2018), although their origins can be traced back to the economic-energy models of the 1970s (Parson, 1997). Integrated Assessment models (IAMs) can be broadly defined as computational models that combine geophysical climate variables with social, economic, and technological assumptions to explore the evolution of GHG emissions and rates of warming under different socio-economic scenarios to support decision-making (Weyant, 2017). Analysing the rise of IAMs in the science-policy interface from 1970 to 2015, van Beek et al. (2020) emphasize that the breadth and adaptability of IAMs, alongside trends favouring quantitative knowledge and advances in computer technologies allowed IAMs to fulfil diverse roles in addressing climate issues over time, ranging from agenda-setting to monitoring political ambition for mitigation.

Nowadays, IAMs comprise a wide range of models that differ tremendously in their structure, complexity, level of detail, use, and representation of impacts. Global-scale IAMs for climate change mitigation can be broadly categorized as benefit-cost (or simple) and detailed-process (or complex) IAMs. Broadly speaking, benefit-cost IAMs provide aggregate representations of mitigation costs and impacts through a single economic metric (such as the social cost of carbon). Detailed-process IAMs, on the other hand, seek to provide a mode disaggregated projection of the effects of climate change with the use of either economic valuations or projections of physical impacts (Weyant, 2017). The IPCC's Working Group III relies on inputs from detailed-process IAMs as the main methodological approach for the articulation of global mitigation pathways. The latest AR6 database contains 3131 scenarios generated by different model versions from more than 50 model families (Riahi et al., 2022).

IAMs and the IPCC

As the intergovernmental body of the United Nations tasked with providing policymakers with regular scientific assessments on climate change, its impacts and potential responses (IPCC, n.d.), the IPCC operates at the interface of scientific assessment and policy advice. It serves as a site of negotiation between science and politics (Beck and Mahony, 2018b; Hulme, 2016). It is a dynamic frontier where the boundaries between the two are continuously negotiated (Cointe and Guillemot, 2023; Fogel, 2005; Livingston and Rummukainen, 2020; Lövbrand, 2009), and scientific expertise, or rather the exclusivity in the interpretation of scientific findings (Jasanoff, 1990) is enacted to inform policymaking.

Since its creation in 1988, the IPCC has produced six assessment reports and fourteen special reports on specific topics. In the mid-1990s, most climate modelling efforts were undertaken in conjunction with the IPCC process (Hausfather et al.,

2020) and by the year 2000, the IPCC published a Special Report on Emissions Scenarios (SRES) which included demographic, technological change, and economic development variables as driving forces of future emissions, aiming to assess different possible future storylines and the most cost-effective alternatives to reach different temperature goals (IPCC, 2000). These SRES then fed the IPCC Third and Fourth Assessment Reports. However, for AR5, it was decided that the role of the IPCC would shift from producing scenarios to assessing them, which means that the IPCC's independence as an assessor was given priority over its knowledge production. The IPCC then commissioned the IAM community to produce scenarios under certain guidelines (Beck and Mahony, 2018b).

The Representative Concentration Pathways (RCPs), introduced in the context of AR5, were primarily aimed at assessing the impacts of various climate policy options, using radiative forcing targets as the endpoint, i.e., the amount of energy added to the climate system. Meanwhile, the Shared Socioeconomic Pathways (SSPs), formulated in anticipation of AR6, provide narrative descriptions of several potential societal futures and allow for the exploration of diverse emission trajectories (O'Neill et al., 2017; Riahi et al., 2017). The SSPs are based on five storylines describing different socio-economic development alternatives for the future, including sustainable development, regional rivalry, inequality, fossil-fuelled development, and middle-of-the-road development (O'Neill et al., 2017)

While RCPs focus on emissions scenarios and radiative forcing, SSPs consider broader socioeconomic factors, and work side by side in IAMs to provide complementary insights to explore policy-relevant mitigation options under different emissions and societal development trajectories. Hence, with the Paris Agreement, the role of the IPCC WGIII shifted away from identifying the causes and effects of global warming to projecting potential policy solutions to reach specific temperature targets, and the use and construction of IAMs shifted from looking at the attribution of causes and detection of impacts of climate change, to a more solutions oriented and policy-relevant assessment of future climate trajectories (Beck and Mahony, 2018a).

The request made during COP21 in Paris for the IPCC to prepare a Special Report on 1.5°C of warming marked a significant shift in the role of science for policy. While the emergence of the 2°C Paris target reflects the collaborative relationship between science and policy over time (Livingston, 2018; Lövbrand, 2011), the consideration of the 1.5°C target by the IPCC and the broader scientific community only happened because it gained political approval (Cointe and Guillemot, 2023; Livingston and Rummukainen, 2020). In this Special Report "all pathways" required the deployment of large-scale CDR to keep the 1.5°C target within reach. To gain a deeper understanding of the performative role and potential implications of CDR in mitigation scenarios, it is important to first have a critical understanding of the modelling dynamics that brought it to the table and the assumptions they entail.

Surveying the landscape of modelling critiques

In parallel to the growing prominence of models over the years, there has been a sustained body of literature critically scrutinizing the assumptions and choices in models, their methodological limitations and their uses and relevance in informing policy (Pedersen et al., 2022). When designing scenarios, modellers need to make a series of choices to account for the pervasive social, economic and scientific uncertainty that models are built on (Beck and Krueger, 2016; Haikola et al., 2019b; Pindyck, 2017). Consequently, the results of the models are heavily dependent on the assumptions and structure of the models (Beck and Krueger, 2016; Gambhir et al., 2019; Peace and Weyant, 2008; Rosen and Guenther, 2015), any changes in these inputs can provide very different results in the scenario context. Therefore, deciding on and including certain assumptions makes the development of models a fundamentally political exercise.

In mitigation scenarios, the IPCC, as well as modellers, have been adamant that future emission trajectories are the product of complex social, environmental, technological, political, and economic dynamics. Modelled scenarios are not meant to be predictions of how the future will look, but rather potential alternatives of how the future could look, under different policy considerations, parameters, and assumptions. Yet, although the modelled mitigation scenarios and pathways assessed by the IPCC aim to be policy-relevant but not policy prescriptive, by being asked to assess the performance of policies in the future numerous challenges emerge in what Beck & Mahony (2018) have referred to as the politics of anticipation. Mitigation models not only envision, but also ‘perform’ certain futures, and the IPCC, through its role at the interface between science and policy, contribute to the stabilization of particular ways of imagining climate policy and action by presenting them as globally plausible options (Beck and Mahony, 2018b; Hughes and Paterson, 2017; Miller, 2001), while, at the same time, limiting the possibility of imagining alternative visions of mitigation futures (Beck and Oomen, 2021; Hulme, 2011). BECCS, for instance, was largely absent from policy discussions until it appeared in IPCC mitigation scenarios (Carton, 2020a; Haikola et al., 2019b).

While scholars have critiqued some choices in the models as being arbitrary (Pindyck, 2017), others have challenged this view by arguing that instead, these assumptions reflect the values and preferences of modellers in the face of uncertainty and the prevailing social relations within which they are embedded (Beck and Krueger, 2016). This then contributes to reinforcing and reproducing existing societal discourses and values (Carton, 2019, 2020a; Ellenbeck and Lilliestam, 2019), unjust power dynamics and limited visions of the future (Beck and Mahony, 2018a, 2017).

For instance, a study examining the institutional dynamics, social scientific networks, and patterns of Authorship of the IPCC’s WGIII for AR5 highlighted the prevalence of US and UK institutions as training sites for WGIII authors; and showed that co-authorship is common among few researchers, which ultimately influences the IPCC's approach to mitigation (Corbera et al., 2016). A subsequent study highlighted the dominance of a small group of authors and institutions from the Global North in WGIII. "Of the 38 most cited authors, 25 of them are based in the EU, 11 are in the United States, and 2 are from BRICS countries (Brazil and South Africa, specifically), with none outside these three groups. Even for the entire writing team, citations are dominated by EU authors, with 53% being of EU-based authors, 28% of North Americans, 9% from BRICS countries, and only 10% from the rest of the world." (Hughes and Paterson, 2017, p.751). With regards to disciplines, these teams predominantly consist of economists, engineers, physicists and natural scientists, while the social sciences and humanities are largely underrepresented (Corbera et al., 2016; Hughes and Paterson, 2017). Moreover, IAMs are rarely independent from each other: the modelling community commonly shares code and data, while depending on multiple layers of comparable inputs and assumptions. Additionally, a limited number of high-profile models tend to dominate the territory. In AR6, 90% of scenarios were produced by only 8 model teams (Riahi et al., 2022).

However, the much-needed careful consideration of the geographic and disciplinary biases and assumptions in models gets lost in translation when modelled scenarios reach policy spaces. Due to their inherent complexity, understanding the implications of the different parameters, assumptions and outcomes is not an easy task for those outside the research/modelling community. Moreover, the growing granularity in models that allowed IAMs to be the leading scientific tool for climate change mitigation, has made it more difficult to be understood and scientifically scrutinized (Robertson, 2020). This task grows in difficulty as the models' algorithms incorporate new features and variables (Revesz et al., 2014; Rosen, 2015). The challenges of scrutability and verification have prompted the qualification of models as 'black boxes' (Haikola et al., 2019b; Pfenninger, 2017). A black box is a device or system bracketed as an instrument to perform a specific function deemed valuable by an institution or society at large, without the need to understand what goes on inside of it, and therefore neglects any detailed account of their structure, inner workings and social origin (Winner, 1993). Both the IPCC and the modelling community have made efforts to improve transparency and open this "black box" (Skea et al., 2021).

IAMs are sometimes described as economic models of climate change, as most – if not all – seek to outline the most cost-effective ways of achieving mitigation outcomes. The economic framework within IAMs closely adheres to neoclassical economic principles, emphasizing rational choice theory, utility maximization, access to perfect information, and fully functioning markets – among other things – as parameters to understand and evaluate decision-making (Ackerman et al., 2009a; Ellenbeck and Lilliestam, 2019; Keen, 2020). It is precisely in many of these economic parameters and assumptions, where numerous biases and value-laden assumptions can be examined.

Discussions on the evolving relevance – and the economics – of the integrated assessment models of climate change are incomplete without mentioning the work of William Nordhaus, whose effort to develop a cost-benefit tool for global mitigation policy analysis granted him the 2018 Nobel Memorial Prize in Economic Sciences. Nordhaus pioneered the development of a Dynamic Integrated Climate and Economy (DICE) model, a globally aggregate general-equilibrium model of the economy and the climate system to determine optimal mitigation policy regarding abatement costs and climate damages (Nordhaus, 1994). This model is fundamentally different to the models that inform the IPCC reports nowadays, but it has played an important role in influencing international climate negotiations in the early days and informing national climate policy in e.g. the United States (Fisher-Vanden and Weyant, 2020). Scholars have extensively scrutinized the problematic assumptions, omissions, and consequences within the economics of the Nordhaus model (Asefi-Najafabady et al., 2020; Hickel, 2018; Keen, 2020). While certain concerns are unique to this model, many of the criticisms are representative of broader issues found in the economics used in other types of IAMs.

The IPCC Special Report on 1.5°C was released the day before the Nobel Prize was awarded to Nordhaus. Paradoxically, during his Nobel Prize acceptance speech, he suggested that a 4°C increase in global average temperature would be economically optimal. Then, in a follow-up scholarly article derived from this lecture, he even suggested that the loss of economic growth would be negligible even under 6°C of warming (Nordhaus, 2019). These calculations are grounded on several simplifications and assumptions, including the fundamental disconnect between economic assessment and the earth and climate systems, resulting in the utter underestimation of the social and ecological impacts of a changing climate, including an omission of the tipping points in the Earth System. In some benefit-cost scenarios produced with Nordhaus's DICE model, 87% of the US economy is excluded from the economic impacts of climate change because they take place in 'carefully controlled environments', i.e. indoors, and would not be affected by climate change (Keen, 2020).

The use of discount rates is one of the most largely debated issues in the climate-economy modelling literature (Ackerman et al., 2009b; Arrow et al., 2013; Dasgupta, 2008; Stern, 2006). Discount rates determine how much society should spend on mitigation today to limit the impacts of climate change in the future. When creating long-term scenarios, small variations in this rate lead to largely different policy recommendations. The choice of discount rate is fundamentally ethical and normative; and is largely driven by economists' views on intergenerational justice (Dasgupta, 2007). The Stern-Nordhaus debate on the use of discount rates in economic models of climate change is a clear example of this. While Nordhaus has long advocated for a high discount rate arguing that failing to maximize growth by spending money to address climate change would not help future generations (Nordhaus, 2019), Stern (Stern, 2006) advocated for a low discount rate (1.4%) in favour of immediate action to reduce emissions, reflecting the urgency to address climate change in the short term. Most IAMs assessed by the IPCC use discount rates of 5-6% (Emmerling et al., 2019), which prioritize economic value in the short term by assuming an expectation of robust economic growth and favour slow incremental mitigation in the short term (Ackerman et al., 2009a; Carton, 2019; Freeman and Groom, 2016; Revesz et al., 2014). This transfers the burden onto future generations, particularly affecting the most vulnerable populations among them (Shue, 2017). This is especially concerning given the tendency for past economic forecasts to overestimate growth (Burgess et al., 2020; Slameršak et al., 2024), and underestimate or completely disregard the impacts of climate change already happening below 2°C (Schultes et al., 2021).

In their parameters, IAMs also have a tendency to ignore – or attempt to place an economic value on – other dimensions of human well-being that are intrinsically non-monetizable, like life, health, and biodiversity (Ackerman et al., 2009a). Besides, by relying on aggregation, where the general well-being is equated to the sum of the well-being of all members of a generation, they reduce generational well-being to the aggregate levels of consumption (Dasgupta, 2007). Furthermore, by assuming 'fully functioning markets and competitive market behaviour', they ignore existing asymmetries and power imbalances (Carton, 2020a), and assign less value to people in poorer countries (Pindyck, 2017).

In the context of uncertainties on climate sensitivity, several studies have pointed out that IAMs have a tendency to underrepresent, or completely ignore the impacts of unabated climate change, feedbacks, tipping points and high-impact low-probability extreme or catastrophic events, and their corresponding socially contingent impacts (Asefi-Najafabady et al., 2020; Bistline, 2015; Kaufman, 2012; Weitzman, 2011, 2009). Most IAMs considered for AR5, for instance, exclude high-impact low-probability natural and social extreme events (Stern, 2016). This showcases a fundamental disconnect between mainstream economic thought and earth systems – and climate – science. I delve further into this issue in Paper I.

Integrating Carbon Removal

The presence of large-scale land-based carbon removal in mitigation pathways was elicited by their economic optimization goal, rather than a thorough technical, political and social assessment (Fuss et al., 2014; Perkins et al., 2023). The use of high discount rates (Emmerling et al., 2019; Köberle, 2019), incrementalistic techno-economic narratives (Carton, 2019; Markusson et al., 2018), and feasibility within model structure allowed for BECCS and Afforestation to appear as new cost-effective alternatives in long-term mitigation pathways (Anderson and Peters, 2016; Fuss et al., 2014; Vaughan and Gough, 2016; Workman et al., 2020). The use of

CDR in models expands the carbon budget into the future, while lowering mitigation costs throughout the 21st century. It also allows for temperature overshoot to be later compensated by substantial carbon removal over the century (Malm and Carton, 2024). Thus, making it more politically appealing to rely on heavily discounted BECCS in the future, rather than investing in deep mitigation now (Anderson and Peters, 2016). Yet, if future deployment fails to scale, society would be locked in a high temperature pathway with catastrophic consequences on the well-being of present and future generations. Therefore, the over-reliance on future CDR presents us with the Catch-22 between overshoot or massive CDR deployment at a scale that might never even be possible in the first place.

Following this line of arguments, McLaren and Markusson (2020), argue that the prominence of CDR (BECCS) in models is the latest technological promise incorporated in the models as a cheaper future climate change mitigation option in response to (but also in support of) ineffective mitigation action in the recent past and present. This action of delaying effective emissions reduction in the promise of future technological improvement is commonly referred to as "mitigation deterrence" (Carton et al., 2023; Markusson et al., 2018; McLaren, 2020). Similarly, Kevin Anderson also argues that “Their [the main IAM groups] low carbon futures are locked into tech-dominated versions of the present with no changes to core political elements or values of society in relation to fairness, or distribution of resources or power. Such tight political criteria, combined with very small carbon budgets, force all mitigation scenarios assessed by the IPCC to include increasingly extreme levels of CDR.” (Anderson et al., 2023 p.809)

BECCS first emerged over two decades ago (Keith, 2001) as a risk management idea (Obersteiner et al., 2001). It then captured the attention of the IAM community for the exploration of mitigation pathways consistent with 2°C, where it increasingly gained importance to eventually become a key feature in IPCC policy-relevant mitigation pathways (Beck and Mahony, 2018a). BECCS involves generating energy by burning biomass (from residues and dedicated energy crops), which sequestered carbon during growth, then capturing the CO2 emitted during the energy generation process, and storing it permanently underground through Carbon Capture and Storage (CCS). Yet, although CCS has been part of mitigation portfolios for almost two decades, it remains an emerging technology. Therefore, despite being far from commercial deployment, BECCS took a leading role in models as it combines two already known mitigation options that fit well into the structure of the models: Bioenergy generation and Carbon Capture and Storage (CCS). These options also optimize two modelling parameters: energy generation and carbon sequestration (Fuss et al., 2014).

At scale, the widespread implementation of Bioenergy with Carbon Capture and Storage (BECCS) and Afforestation/Reforestation (A/R) that is assumed in models would unavoidably demand extensive land use changes. Numerous studies have highlighted potential conflicts with land uses, food security, biodiversity loss, and ecosystem feedback associated with land-intensive CDR methods (Boysen et al., 2017; Deprez et al., 2024; Dooley and Kartha, 2018; Fuss et al., 2018; Heck et al., 2018; Shukla et al., 2019; Smith et al., 2016). Furthermore, as the spectrum of scenarios is broad, the inclusion of extreme and unrealistic scenarios – like those requiring the land of all tropical and subtropical forests and savannas to fulfil BECCS requirements – make less extreme scenarios seem plausible (Creutzig et al., 2021). Further, scenarios and policies often fail to recognize that the widespread assumptions that biofuels are carbon neutral respond to simplifications in carbon accounting (Johnson, 2009; Ramos, 2022), and that removing forest carbon stocks for bioenergy leads to an initial increase in emission and long payback times (EASAC, 2022; Norton et al., 2019). Another important aspect is that some land use changes could cancel out the carbon removed by BECCS, for instance, if biomass plantations are replacing high-carbon ecosystems (Harper et al., 2018; Holtsmark, 2013).

Estimates vary largely regarding the volumes of CDR required under different scenarios. Although the scale of CDR needed would ultimately depend on the rate of emissions reductions, CDR requirements in recent studies range from 1.5-3 to 4.7-10 GtCO2/yr by 2050 (Smith et al., 2023). Some estimates suggest that each yearly gigaton of CO_2 removed with BECCS would require around 30 to 43 Mha of cropland for biomass production, and removals of 10 Gt/y CO_2 with BECCS would require 40% of all global cropland areas (NAS, 2019). Others indicate that the median rate of bioenergy crop expansion would need to be three times greater than the historical rate of expansion of soy – the fastest growing commodity in the world (Turner et al., 2018). In AR5, the vast majority of scenarios that meet the goals of the Paris Agreement exceeded sustainability and precautionary thresholds in land and BECCS (Creutzig et al., 2021). In the IPCC SR1.5, the use of CDR (mainly BECCS) was projected in the order of 100–1000 $GtCO_2$ over the century. Following controversies over the overly optimistic expectation for BECCS in previous assessments, scenarios for AR6 explored ways to restrict deployment (Grubler et al., 2018; van Vuuren et al., 2018), although BECCS continues to be the leading CDR method in most scenarios. At present, only $2GtCO_2$ are being removed annually, with almost all attributed to traditional land-use, land-use change, and forestry practices. Novel forms of CDR constitute merely 0.01% of removals, with BECCS contributing to removals of 0.00182 $GtCO_2$/yr (Powis et al., 2023).

Further, although there are high uncertainties concerning the feasibility, scalability and location of CDR methods, most modelled scenarios and net-zero plans anticipate the large-scale deployment of land-intensive methods in the Global South (Bluwstein and Cavanagh, 2023; Dooley et al., 2022; Jaschke and Biermann, 2022). A/R in models is often restricted to temperate and tropical zones (Kreidenweis et al., 2016; Strefler et al., 2021) because of the potential warming effects of biomass expansion in boreal zones resulting from changes in albedo from afforestation in higher latitudes, thus potentially offsetting the cooling from carbon sequestration

(Mykleby et al., 2017). In addition, under the global techno-economic and cost-efficiency logic of models, biomass plantations are more feasible in areas of the Global South where land is cheaper and climatic conditions might be more favourable for plant growth. As Fuhrman et al. (2019) point out, some models anticipate the conversion of major portions of sub-Saharan Africa (Calvin et al., 2019) and some parts of the northern hemisphere into major agricultural regions to scale up biofuel production in mitigation scenarios (see also Hansson et al., 2020). Other models anticipate similar land use changes in large areas of the legal Amazon and the Brazilian Cerrado (Fuhrman et al., 2019; Hurtt et al., 2020).

Theoretical Framework

This thesis is informed by a social constructivist approach to knowledge production. It departs from the notion that the act of producing knowledge is inextricably linked to a specific social, material, cultural, and political context (Jasanoff, 2004; Latour, 1993), and therefore, science and politics can never be fully separated. This approach to knowledge does not challenge the existence of phenomena but contends that our understanding of reality is constrained by how we represent it. Social constructivism emphasizes the social and subjective aspects of scientific practice (Latour, 1987; Polanyi, 1958), which facilitates a critical examination of the effects generated by specific ways of knowing. Theoretically, I draw on insights from Science and Technology Studies (STS), and Political Ecology. Justice is also central in the analytical framing of this thesis.

The Politics of Knowledge

Decades of scholarship in interpretive and critical social sciences have discussed the intricate relationship between science and decision-making. Scholars have argued that knowledge is never completely pure, simple, value-free and ahistorical, but rather 'situated' (Haraway, 1988), and co-produced in the social and political order where it emerges (Jasanoff, 2004; Latour, 1987; Mahony and Hulme, 2018).

Studying the politics of knowledge entails analysing how social and economic interests, material and institutional structures, and power dynamics influence the production, dissemination, and utilization of scientific knowledge, and how scientific, and technological knowledge influence these in return. In broad terms, I understand politics as the exercise and distribution of power in society facilitated and mediated through material, social, cultural, institutional, and discursive means. I define knowledge as the understanding, skill or information acquired through study or experience. Knowledge can exist in various forms. Polanyi (1966) distinguishes between explicit or formalized/codified knowledge, i.e. academic disciplinary knowledge, and implicit or tacit knowledge, i.e., cultural norms, inherited practices, implicit values, and intuitive judgments. He argues that scientific inquiry and problem-solving involve an interplay of both tacit and explicit knowledge. Knowledge production emerges within a specific societal context, tied to wider historical, social, political, and economic processes (Jasanoff, 2004;

Ravetz, 1987; Scott, 1998); and is therefore unavoidably subjective as it is influenced by human choices, values, theories and methods of research (Latour, 1987; Lövbrand et al., 2015; Sarewitz, 2004; Turnhout, 2018). Thus, both the use and making of knowledge are a political exercise.

Critical studies in science and technology have examined how science, technology, and the social and political order influence – or co-produce – each other (Jasanoff, 2004; Latour, 1993), by focusing on how scientific knowledge is constructed and shaped within the societal system and political context where it emerges, and vice-versa (Hess and Sovacool, 2020; Hulme, 2010; Jasanoff, 2010; Mahony and Hulme, 2018; Winner, 1980). Scholars have also drawn attention to the often overlooked key role of scientists and experts in framing the early stages of policy debates (Ellenbeck and Lilliestam, 2019; Jasanoff, 1990; Latour, 1987).

The Politics of Climate Change Research

Climate Change research often frames climate change as a global problem that requires globally coordinated solutions. This framing frequently assumes an all-encompassing and normative view of globally shared values, interests, and visions of the future. This 'global gaze' (Jasanoff, 2001) of climate change is informed – and achieved – by algorithmic models, satellite imagery and geological data, which elicited the possibility of imagining the climate as something computable and manageable (Edwards, 2010; Hulme, 2014). This science-based, albeit simplified global formulation of policy-relevant climate research masks the social and epistemic commitments implied in scientific practices, and serves to dissociate the physical properties of greenhouse gas (GHG) imbalances from the social relations and structures that produce them (Demeritt, 2001). These formulations have historically reinforced dominant narratives and social power structures in climate policymaking (Bäckstrand and Lövbrand, 2006; Fogel, 2005; Lövbrand et al., 2015).

Moreover, in climate change, and environmental policy in general, science is often expected to provide the appropriate objective foundation to inform the policy roadmap. Research in policy-relevant environmental knowledge has drawn attention to the ways in which knowledge exercises power, by examining the cultural, historical, political and material context in which particular understandings of reality emerge (Lövbrand et al., 2015; Robbins, 2003; Turnhout, 2018). Studies have shown that rather than solving controversies, scientific justification is often used to reinforce value disputes and competing interests (Douglas, 2009; Sarewitz, 2004), that scientific consensus does not prevent contradictory policies (Grundmann, 2007), or that uncertainty can serve as a justification to serve particular interests and political agendas (Conway and Oreskes, 2010). In the science-policy interface, where the boundaries between science and politics are being constantly negotiated (Jasanoff, 1990; Miller, 2001), scholars have also examined the implications that scientifically informed visions of the future can have in the present (Beck & Mahony, 2018a; Edwards, 2010; Jasanoff & Kim, 2015).

Co-producing Knowledge

The concept of co-production is interpreted differently across various disciplines, traditions, and science-policy domains (Bremer and Meisch, 2017; Miller and Wyborn, 2020). It is often understood as: i) a process of co-generation of knowledge between diverse stakeholders and forms of expertise (IPBES, 2016; Lemos and Morehouse, 2005; Ostrom, 1996) or; ii) an analytical approach to dealing with the relationship between the production of science and the social order (Jasanoff, 2004; Latour, 1993). Tensions between these two – utilitarian and critical – forms of knowledge co-production frequently manifest in the science-policy space (Lövbrand, 2011).

My analysis is informed by the latter more critical/reflexive idiom of co-production, understood as an analytical approach to examine how science, technology, and the broader social and political environment interact and shape one another. I draw on performativity and co-productionist accounts of STS by looking at the ways in which scientific knowledge production contributes to shaping the societal phenomenon it seeks to understand (Jasanoff, 2004; Turnhout et al., 2016). In other words, how scientific knowledge can have the performative capacity to influence and construct its own social reality.

The use of co-production as an interpretative framework allows me to consider the unavoidable and often implicit assumptions and worldviews that shape which and how knowledge is gathered and prioritized and for what purpose (Beck and Mahony, 2018a; Jasanoff, 2004). Further, it allows me to uncover the historical and social processes that influence the production of scientific knowledge that might tacitly contribute to enhancing and perpetuating hegemonic interests, and render other forms and sources of knowledge invisible (Forsyth, 2022; Lövbrand et al., 2015). This involves focusing on the construction and development of knowledge in relation to the societal, environmental and political economic contexts in which it arises (Lave, 2012), as well as the reciprocal impact of science and technology on society (Hess and Sovacool, 2020; Hulme, 2010; Mahony and Hulme, 2018).

What Climate Futures?

A central focus of this thesis is the exploration of how conceptions of the future emerge (Paper I), are mobilized, and become forces of action in the present (Paper II and III). Departing from the political framing of knowledge production, I investigate both the performative role and the potential real-world implications of carbon dioxide removal technologies as envisioned in modelled mitigation scenarios. A valuable approach to investigating the materialities and socio-ecological dynamics that visions of a future with large-scale CDR can entail is to critically examine the different components of these socio-technical transformations within the local contexts where they are emerging or expected to emerge. To do this I focus my analysis on two key requirements for large-scale CDR – as projected by the models – i) the significant need for land – studied empirically based on a real-world heuristic case study – and ii) Carbon Capture and Storage (CCS) as a critical technological component for BECCS (and other mitigation and CDR methods) – studied based on emerging policy. This is explained more in depth in the methods section.

I draw on insights from Science and Technology Studies (STS) and put them in conversation with Political Ecology and Justice to inform the analysis of the empirical data. Research in STS has provided valuable insights into the co-production of knowledge and society, and the social aspects of science and technology. Yet, while it has looked at the political role of the production of science, technology, society, and the role of expertise, limited attention has been paid to the material and ecological dimensions of these science-society dynamics. Research in Political Ecology, on the other hand, has been mostly interested in the use of science in resource conflicts (Lave, 2012; Robbins, 2004). Scholars in political ecology seek to understand and explain the underlying causes of environmental change and have for decades illustrated how asymmetrical political-economic relations and structural inequities significantly influence environmental governance practices and lead to injustices and unequal power dynamics in decision-making (Chomba et al., 2016; Hecht, 1985; Heynen and Robbins, 2005; Ingalls and Dwyer, 2016).

More broadly, research in Political Ecology has examined the intricate relationship between politics, economics and the environment (Robbins, 2004), and the ways in which socio-ecological struggles shape resource distribution (Ahlborg and Nightingale, 2012; Carton, 2020b; Robbins, 2003). In addition to this, Political Ecology has a longstanding engagement with conflicts and struggles in the Global South, while STS research has predominantly focused on North America and Europe. Insights from these two academic debates contribute to a comprehensive analysis of how specific understandings of a problem can contribute to tacitly reinforcing uneven power relations and patterns of injustices.

Both Political Ecology and STS are valuable for analysing and gaining a deep understanding of the intricate societal relations between society, the economy-ecology and science. The inherent complexity and context-based nature of these insights offer an opportunity for a nuanced understanding of the numerous aspects and politics at play in the context of policy-making efforts and societal interventions. While this may not lend itself to straightforward, one-size-fits-all, context-free and technicalized solutions that easily appeal to policymakers and practitioners, it underscores the importance of deep engagement and thoughtful consideration in addressing them. Therefore, rather than striving for prescriptive formulas, scenarios and policy recommendations, my thesis aims to highlight these complexities, encouraging fellow researchers to delve into the intricacies and contribute to the advancement of policy-relevant research in a meaningful and equitable manner.

Imaginaries of land and carbon

Land-use change dynamics and underlying as well as emerging social conflicts have been extensively studied by political ecology. In Paper II, I mobilize the STS concept of sociotechnical imaginaries to study the ways in which national political orders and techno-scientific projects co-produce each other in the context of accelerated land use change in the recent past and present, in analogy to those prospectively expectable from the large-scale employment of land-intensive carbon removal methods. In combination with insights from political ecology literature on land-use change, this approach allows me to dive into the material implications of future visions of climate mitigation. In doing so, I explore how visions of futures are far more than simple discursive abstractions, but often emerge within the context of certain socio-economic realities that can solidify specific path dependencies that further reproduce, perpetuate, and entrench the conditions in which they emerge.

Sociotechnical imaginaries (STI) are "collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology" (Jasanoff & Kim, 2015, p.4). The IPCC, as the organization in charge of assessing the state of global climate knowledge (Beck and Mahony, 2018b; Hughes and Paterson, 2017; Miller, 2001), contributes to the stabilization of particular imaginaries by presenting them as global policy-relevant options. Sociotechnical imaginaries embed promises, visions and expectations of a collective future and influence policy independently on whether they materialize or not. These imaginaries are also deeply entangled in larger social, political and economic processes (Jasanoff and Kim, 2013) and often serve to legitimize societal structures and perpetuate the status quo (Delina, 2018; Kuchler, 2014). As products and means of the co-production of science, technology, and society in modernity, imaginaries simultaneously describe desirable futures, and delimit attainable futures (Jasanoff and Kim, 2015). Enduring sociotechnical imaginaries can shape the ways in which nation-states understand and allocate risks and opportunities for large development projects (Christiansen and Carton, 2021; Delina, 2018; Jasanoff and Kim, 2013, 2009; Neimark, 2016). Further, sociotechnical imaginaries can help to make sense of the temporal and scalar shifts in the collective understanding of environmental problems (Ramos, 2022).

Studying the impacts of large-scale CDR challenging as no methods have even been deployed at scale, although lessons can be learned from the long history of climate mitigation (Carton et al., 2020), or through proxy analyses of other societal efforts (Buck, 2020, 2016; Hansson et al., 2020). Through the analytical framework of STI, I examine the role of knowledge translation in shaping the emergence of new national hegemonic imaginaries and their interaction with pre-existing ones. I apply the STI framework in the context of my empirical analysis of accelerated land use transformation presented in Paper II, specifically to study (i) how the translation of knowledge contributes to the emergence of new imaginaries (with CDR) and (ii) how these then interact with pre-existing imaginaries. This application of the STI framework constitutes an important theoretical strength of my thesis.

The politics of technology: Storing carbon

In addition to the land use concerns inherent to large-scale biomass production, BECCS, es envisioned in models, is contingent on the efficient scalability of Carbon Capture and Storage (CCS). In Paper III, I study the technological dimension of CDR (BECCS) by scrutinizing the emergent policy context of Carbon Capture and Storage technology for the specific purpose of mitigating climate change.

CDR methods are largely heterogeneous (Minx et al., 2018), with different technical, economic, and biophysical requirements, that might require different modes of governance and institutionalization. Therefore, they cannot be understood solely as technological artefacts or based on techno-economic aspects alone (Hughes, 1986; Winner, 1980), but as socio-technical systems, shaped by social, political and economic forces. Hence, in this study, I understand CCS as a technological component of a broader sociotechnical system, required for the deployment of CDR (BECCS). BECCS, in that sense, is understood as a sociotechnical system that requires broader societal arrangements, infrastructure, institutional and governance practices to operate – and CCS is one of those components (Miller et al., 2013). BECCS, much like other energy systems, is a sociotechnical system that requires not only biomass and CCS infrastructure to operate, but also access to land, land-use rules, legislation, institutions, companies, and human workforce to design, construct and operate the technology. Energy systems can change in response to societal choices, but energy systems can also reshape societal practices, norms, and ways of living. “Over time, these changes can contribute to creating or reinforcing unequal distributions of power and wealth in industrial societies.” (Miller et al., 2013, p.136)

Drawing on theoretical insights from STS research on the politics of technology, the analysis departs from the idea that technology design and implementation is not a neutral endeavour; instead, it reflects – and influences societal values, power structures, and political configurations (Bijker, 2010; Winner, 1980). Winner (1980) discusses two ways in which technologies may have politics embedded within. First, when a technology is closely associated with a certain type of politics, but it is not necessarily inherent to it, and therefore this technology can be utilized in different ways and under certain circumstances. The second one is when a technology is both created with and requires specific kinds of political relations to operate properly. In the first scenario, where a technology can be directed and governed toward different purposes, the initial phases of its implementation are characterized by limited information, which poses challenges in anticipating and evaluating potential societal consequences (Collingridge, 1980). However, this early stage is also when technologies are easier to control and redirect. The dynamics then shift once the technology achieves widespread deployment, becoming more resistant to control and modification as it has already influenced established practices and infrastructure (Collingridge, 1980).

The development of CCS technology has been largely associated with fossil fuel extraction (Loria and Bright, 2021). However, the potential for effectively repurposing it for other uses outside the fossil fuel industry on a significant scale remains an open question. A prominent concern about the use of large-scale BECCS (and other CCS uses for mitigation) in models is that the promise of its future deployment may serve as a discursive and material tool to delay emission reductions and perpetuate the fossil economy (Carton, 2019; McLaren, 2020; McLaren and Markusson, 2020). In the literature, CCS is treated in different ways. In Energy transition debates, the uses of CCS for fossil extraction and for removals are often treated interchangeably (Mascarenhas et al., 2019; Román, 2011). In Integrated Assessment Models, CDR options (mainly BECCS and A/R) come as an additional set of climate change mitigation technologies that compete with existing mitigation options, like energy efficiency, renewables, nuclear energy, and CCS alone (Tavoni and Socolow, 2013), i.e., they seem to exist independently of each other and as technological artefacts without politics. In this context, I here propose and employ an approach to scrutinize the political dimension of a technology – and its feasibility and direction toward specific outcomes – using a critical examination of its transition from theoretical mitigation scenarios to actionable policy proposals (Paper III).

Justice and Equity

Questions of justice and equity are cross-cutting throughout this thesis. I see justice as a fundamental building block in the bridge connecting knowledge and policy and as a strategic propositive entry point for more epistemic diversity in the global political conversation. Justice is central to my analysis in Paper I, where I draw in critical justice theorizations, namely that of Nancy Fraser, to look at the ways justice concerns emerge from modelling exercises. Papers II and III, on the other hand, adopt a more empirical and actionable perspective, where I examine the equity and justice implications of future carbon removal in the coproductionist interaction modelled mitigation scenarios and the way they inform policy – and vice versa-.

Surveying the theoretical landscape of justice

Different philosophical and cultural traditions, legal systems, and ethical frameworks have contributed to the diversity of perspectives and nuanced interpretations of justice within ethical and moral frameworks (Miller, 2023). Traditional academic debates about justice have mainly centred on distributive issues, that is, the fair allocation of resources in society, with different philosophical traditions emphasizing different understandings of how to operationalize distributive justice. These range from the utilitarianism of Bentham and Mill's advocating for the greatest utility for the greatest number of people (Bentham, 1970; Mill, 1893), to Rawl's liberal egalitarianism advocating for equal basic liberties, opportunities, and greater benefits to the least advantaged (Rawls, 1971), all the way to Sen's capabilities approach centred in the capacity of individuals to meet their needs and pursue their goals in life (Sen, 2009, 1970).

While distributional concerns are central to justice, some scholars have argued that theorizations of distributive justice often neglect the social, political, institutional, and overall structural contexts in which conditions for distribution are set (Fraser and Honneth, 2003; Schlosberg, 2004; Young, 2011). Nancy Fraser's trivalent theorization of justice explicitly addresses these concerns by incorporating considerations of recognition and representation into the framework (Fraser, 2010a). It posits that not only a focus on the socio-economic distribution of resources is necessary to achieve justice, but legal, cultural recognition (justice as recognition), and the ability to participate in political and cultural life (i.e., representative, or procedural justice) are also imperative. Additionally, most theorizations of justice have focused on the individual, extendable to political communities demarcated within the bounds of a geographical place. Challenging the notion that justice can only be imagined domestically, Fraser's post-Westphalian framing extends this concern beyond national borders by explicitly dealing with the transnational-to-local dynamics of justice in a globalizing world (Fraser, 2010b). Therefore, I found it to be an adequate theoretical point of departure to analyse equity considerations in the normative underpinnings in the global scope of mitigation scenarios and the use of scenarios to inform policy, which is created and enacted at the national/local level.

Aiming to unveil the tacit assumptions and ethical commitments based on different principles of distributive justice, and drawing from political philosophy, and Nancy Fraser's three-dimensional conceptualization of justice as distribution, recognition, and representation (Fraser, 2010a, 2010b), Paper I, interrogates what principles and dimensions of justice emerge in common critiques of IAMs and which ones remain unnoticed. Paper I also engages with debates on epistemic and cognitive justice to highlight the importance of bringing to the fore other ways of doing and being as a fundamental step to imagining alternative and more equitable futures.

Epistemic justice (Fricker, 2003; Medina, 2017) focuses on the fairness and equality in the production, distribution, and recognition of knowledge within specific societal contexts and epistemic communities. It aims to expose and address biases, inequalities, and power dynamics that shape who is considered a credible knower and whose knowledge is valued and legitimized. Cognitive justice (Santos, 2008) takes this one step forward by focusing on the recognition and validation of diverse knowledge systems and ways of knowing from a broader societal scope. From an analytical standpoint, Santos (2016) links the epistemological privilege granted to (western, positivist) modern science since the seventeenth century, to processes of colonial expansion that entailed the suppression—and extermination—of marginalized social groups and their forms of knowledge. Cognitive justice also often explicitly emphasizes the need for decolonization (Mignolo, 2021; Quijano, 2007).

Equity and justice in climate change mitigation

Equity and justice concerns have become increasingly ubiquitous in the climate policy space, as debates around the causes and impacts of climate change, as well as efforts to address it, continue to give rise to ethical, equity, and justice-related questions (Caney, 2014; Chatterton et al., 2013; Klinsky and Dowlatabadi, 2009; Newell et al., 2021; Okereke, 2010; Okereke and Coventry, 2016; Sultana, 2021). Yet, although climate change poses a severe threat to all of humanity, there is a fundamental recognition that the populations that have contributed the least to creating the problem are the ones that would suffer the most, both within and beyond present generations. Climate justice has been a central mobilizing claim for frontline communities, Indigenous peoples and social movements, Indigenous peoples (ICJN, 2002; IEN, 2012; The Red Nation, 2021). It is also an interpretative framework for a growing body of academic research (Caney, 2014; Forsyth, 2014; Klinsky et al., 2017; Lahn, 2018; Newell et al., 2021; Roberts and Parks, 2006; Schlosberg and Collins, 2014; Shue, 2014; Sultana, 2021; Whyte, 2020).

In the multilateral climate governance regime, justice and equity concerns are encapsulated in the notion of 'common but differentiated responsibilities and respective capabilities' within the UNFCCC and reaffirmed under Article 4.1 of the Paris Agreement. In global debates justice has primarily been approached as a distributional question concerning how to equitably share the effort required to avoid dangerous climate change (Caney, 2009; Dooley et al., 2021; Holz et al., 2018; Klinsky and Dowlatabadi, 2009; Page, 2008; Pan et al., 2017; Winkler et al., 2018).

A spectrum of equity approaches has been explored in the literature, – based on carbon budgets and global emissions pathways (Höhne et al., 2014; Pan et al., 2017, 2014; Raupach et al., 2014; Robiou du Pont et al., 2017; van den Bergh et al., 2020), in an effort to provide quantitative and policy-relevant answers to the inherently normative and ethical considerations of justice and equity (Dooley et al., 2021; Klinsky and Winkler, 2018; Lahn, 2018). These have been based on broadly defined principles around responsibility, need, capacity and equality; as well as costs-optimization and grandfathered approaches, which allocate the carbon budget based on current emissions levels (see Table 1). Moreover, some equity approaches have faced scrutiny for implicitly favouring wealthier countries and perpetuating grandfathered approaches (Kartha et al., 2018).

Table 1. Brief overview of the principles guiding different effort-sharing approaches

Principles	Description
Responsibility	Those who have caused and benefited the most from the activities that cause climate change should bear more responsibility to deal with it. Allocation of efforts based on a country's historical contribution to global cumulative emissions.
Need	Considers a country's specific development needs, and vulnerabilities to allocate efforts and responsibilities.
Equality	Equal emissions rights for all individuals. Allocation of emissions in proportion of population size in the present, considering past emissions, or projected linearly towards the future.
Capacity	Considers a country's level of economic development to allocate efforts. Countries with more ability to pay (higher GDP) and greater capabilities can bear a larger share of mitigation efforts
Cost-optimization	Allocation emissions allowances and mitigation efforts based where they can be achieved most cost-efficiently, independently of past or current emissions and levels of economic development.
Grandfathering	Allocation of carbon budget in proportion of current emissions. Historical emissions are interpreted as acquired rights to justify claims for future emissions entitlements.

Justice and Carbon Dioxide Removal

The emergence of carbon dioxide removal as a necessary activity to reach the Paris temperature targets in models raised numerous concerns about the feasibility and impacts of large-scale CDR (Anderson, 2015; Geden, 2015; Williamson, 2016).

Most assessments on CDR deployment have followed cost-efficiency approaches and techno-economic potentials from IAMs (Riahi et al., 2022; Rogelj et al., 2018). A handful of modelling studies have attempted to explicitly quantify national fair-shares of carbon dioxide removal (CDR) based on the above mentioned equity principles of responsibility, equality, need and capacity (Fyson et al., 2020; Holz et al., 2018; Lee et al., 2021; Pozo et al., 2020), to evaluate how to distribute the burdens of removals – in addition to emissions reductions. However, when examined from the perspective of developing countries, several issues can be identified that favour wealthy nations (Kanitkar et al., 2024; Yuwono et al., 2023), similar to earlier equity allocation studies (Kartha et al., 2018).

Nonetheless, results from modelled assessments have allowed to identify some of the potential socio-ecological and material impacts of CDR, about e.g. land-use competition, land concentration, biodiversity loss, and food security (Creutzig, 2016; Creutzig et al., 2021; Doelman et al., 2020; Fuhrman et al., 2019; Smith et al., 2016; Tavoni and Socolow, 2013). Yet detailed analyses and empirical studies on the governance, and distribution of impacts are still limited, especially when it comes to deployment in the Global South, with some notable exceptions (Bluwstein and Cavanagh, 2023; Hansson et al., 2020; McElwee, 2022).

Similarly, in the policy space, while decision-makers have increasingly accepted ideas of CDR as a necessary step to meet their net-zero plans, explicit conversations on how and by whom it should be delivered have been largely avoided (Fridahl and Lehtveer, 2018; Fuss et al., 2020; Peters and Geden, 2017). Yet, analyses of policy discourses reveal that policy documents often presume CDR deployment in the Global South, furthering concerns about responsibilities and the uneven impacts of both climate change and CDR (Jaschke and Biermann, 2022).

This is where insights from science and technology studies on the role of technology and performative power of knowledge production, in conversation with lessons from socio-environmental concerns and impacts on the ground from political ecology can provide important complementary knowledge to examine the current and potential equity implications associated with CDR. In Paper II, I follow this objective by studying the ways in which future imaginaries emerge from the co-production of scientific knowledge and how a given social order can produce and perpetuate certain invisibilities and historical injustices on the ground. In Paper III, on the other hand, we investigate notions of equity concerning mitigation efforts and CDR by examining the emergence of CCS policies as a first step towards expanding technological carbon removal, stemming from visions, assumptions, and expectation within global mitigation scenarios.

Relevance for Sustainability Science

A central aspect of sustainability science is the study of the interactions between the natural and social systems. Through critical approaches, sustainability science seeks to understand how problems came to be and then looks for solutions with the use of holistic problem-solving theories, drawn from multiple disciplines (Jerneck, et al 2011). Sustainability science is interdisciplinary and increasingly also trans-disciplinary (Jerneck et al., 2011; Persson et al., 2018; Spangenberg, 2011). The methodological and theoretical pluralism of sustainability science is, therefore, broadly perceived as well-suited to dealing with wicked problems such as climate change, that cannot be solved by disciplinary approaches alone. Furthermore, equity is a fundamental component of sustainability and sustainability challenges need to be addressed with a social and ecological perspective together (Leach et al., 2018).

Climate change has often been characterized as a 'Wicked Problem'. Wicked problems, as originally defined in planning theory by Rittel and Webber (1973), have key characteristics that revolve around the notion of problem formulation and solutions. Time is limited; there is no single way to explain the problem, and the nature of the explanation defines the nature of the proposed solution; there is no specific number of potential solutions, and any action will generate new consequences and transform the problem.

The techno-economic definitions and approaches prevail in climate change mitigation research and often disregard the growing calls for climate justice and for the recognition of the lived experiences of climate change (Sultana, 2021). Modelled climate futures and Negative Emissions can be interpreted as a partial solution within 'post-normal science', where values are in dispute, facts are uncertain, stakes are high and decisions are urgent' (Ravetz and Funtowicz, 1993). Carbon Removal technologies and modelled scenarios fall into the discussion of what futures are desirable, what is the role of science and who has the authority to decide. Solutions to wicked problems – such as climate change – require an interdisciplinary and pluralist perspective.

My thesis offers a critical contribution to exposing and showcasing the importance of acknowledging the normativity of policy-relevant knowledge production. Considering the complexity and contested territory of sustainability issues, an awareness of the epistemic and normative assumptions is critical to understand how these assumptions are represented and shaped. But also how they are shaping future research and action and how they can contribute (or not) to a more sustainable (Miller, 2014) and equitable future.

Research design and methods

In this section, I explain and justify the research approach employed in this thesis. I the describe the process of selecting the cases for the study. After that I provide an overview of the cases and delve into the research process, timeline, and the difficulties I encountered. A detailed account of the research design and methods is available in each of the papers.

Bryman (2008) distinguishes between method and methodology, designating the former as the techniques employed by researchers for data collection and analysis, while attributing the latter to concerns about epistemology. Methodology deals with the philosophical assumptions and practices that underpin the research process. I adopt a social constructivist approach in my research, which is grounded on the notion that science, technology and society shape each other (Jasanoff, 2004). I used various qualitative methods of data analysis for my study and followed an iterative approach to research, which involves a retroductive exploration between the existing theories and research questions, and the newly emerging qualitative data (Ragin and Amoroso, 2019). Findings and gaps identified on the initial literature review (Paper I) allowed me to conceptualize and design the empirical aspects that followed in the research process (Papers II and III). Table 2 shows the methodological approach of each paper.

Table 2. Approach on each paper

Paper	Unit of analysis	Method
(In)justice in modelled climate futures: A review of integrated assessment modelling critiques through a justice lens.	Academic literature	Literature review
Paper II **Imagining large-scale carbon removal in tropical savannas: Lessons from land-use change in the Brazilian Cerrado. (**	Expert Interviews Policy documents Grey literature (NGO reports)	Proxy case study Content analysis
Paper III **From the rainforest to the Fjords: Equity in Carbon Capture and Storage policy.**	Policy documents related to: Energy, CCS legislation, climate change mitigation	Comparative (two-country) case-study Thematic document analysis

The study of Carbon Dioxide Removal has been largely dominated by quantitative methods, like modelling studies and techno-economic feasibility assessments. The qualitative focus of my thesis is a deliberate effort to bring an empirical contribution to this academic debate mostly happening at a global level and dominated by large dataset, algorithmic and quantitative methods (like IAMs). Qualitative research methods are essential to explore complexity and provide a more comprehensive and in-depth understanding of complex societal phenomena (Gobo, 2005). Qualitative research provides insights into aspects often invisible to quantitative approaches. It is also well-suited for accessing tacit and taken-for-granted understandings derived from quantitative methods of inquiry. Thus, in relation to quantitative methods, qualitative research can play a crucial role in explaining, elucidating, and reinterpreting quantitative data, allowing researchers to challenge assumptions and generate new insights (Tracy, 2019). Doing so not only enriches the scholarly debate, but also holds critical practical applications, especially in processes oriented towards informing decision-making and societal interventions, like climate change mitigation action.

I begin this research by examining the ways in which modelled mitigation scenarios deal with justice in a literature review of papers that provide a critical perspective on climate models and the process of modelling. This leads to the conceptualization of Paper I. Using a three-dimensional justice framework grounded in political philosophy (Fraser, 2010a), I review critical literature on Integrated Assessment Modelling (IAMs). The motivation behind this research stems from the recognition that, while IAMs aren't explicitly designed to address justice, their underlying assumptions, parameters, and methodologies inherently embed justice implications that need to be acknowledged and made explicit.

Systematic literature searches in Web of Science and Scopus provide a starting point to identify common critiques and limitations of modelled mitigation scenarios and pathways. Using broad search terms (not only justice-related) allows me to identify critiques from different angles and to analyse their implications based on distributive, recognitional and representational (procedural) justice considerations. This initial choice of terms provided an ample spectrum of critiques and additional literature was added through snowballing from the references of the papers identified, until a saturation of arguments was reached. This approach allows me to bring an explicit focus on the treatment, exclusion and justice implications stemming from IAM scenarios; but also, to show how current criticisms of IAMs tend to foreground certain justice concerns at the expense of others. Building upon the gaps and issues identified in the literature review that led to Paper I, I conceptualize and designe the empirical aspect of the research that followed (Papers II and III). Using case studies provides for an in-depth analysis to a debate primarily unfolding at the global level.

Selecting a case study

A case can be described as "a mental, or analytical, construct aimed at organising knowledge about reality in a manageable way" (Lund, 2014, p.224). Case studies can provide both generalizable insights and an in-depth understanding of specific phenomena (Flyvbjerg, 2006; Johansson, 2007).

As part of the research design for this thesis, I use an embedded case study methodology. Embedded case studies involve an in-depth examination of multiple cases, or sub-units of analysis. The purpose of an embedded case study is to provide an in-depth understanding of particular details and complexities within the broader scope of the research, through the examination of multiple units of analysis (Yin, 2003). In other words, it allows for the exploration of specific cases in detail while considering their relevance to the overall research aim and objectives. As CDR has not been deployed at scale, I examine two key components of carbon dioxide removal in models (A/R and BECCS): land use (Paper II) and Carbon Capture and Storage (Paper III). However, as these are presented individually in two research articles, if one is to look at them as stand-alone cases, i.e. as independent papers, then they stand as critical case studies as they investigate a specific case of strategic importance in relation to the broader problem (Flyvbjerg, 2006). Both cases offer critical insights indicative of justice and equity issues, concerns and impacts that might emerge elsewhere in the world.

Research site and case study selection

Context: Brazil and its global relevance for climate change mitigation

The case of Brazil is particularly instructive for my analysis due to its position as a developing/Global South country, an emerging economy, and a megadiverse, rainforest nation. Brazil is South America's biggest economy and the sixth largest GHG emitter in the world, considering production-based, or territorial emissions. More than two-thirds of Brazilian emissions come from land-use and are relate mainly to deforestation, agriculture and livestock (SEEG, 2022; SIRENE, 2022), with deforestation being the largest contributor of the three. Unlike other major emitters, Brazil has one of the least carbon-intensive energy systems in the world, as around 80% of its energy requirements are met by renewables (IEA, 2022). However, Brazil also ranks among the ten largest oil-producing countries in the world, with ambitions to become the fourth largest global producer. Brazil is also the second largest producer of bioenergy in the world, after the USA, and leads BECCS – and CCS – research capabilities in Latin America and the Caribbean (Machado et al., 2021; Moreira et al., 2016; Restrepo-Valencia and Walter, 2019; Román and Schott, 2011).

Historically, Brazil has also been a key player in voicing equity concerns and bringing issues relevant to the Global South to the international climate negotiation table. For example, with regards to equity in the Kyoto Protocol (UNFCCC, 1997), and more recently at COP28 with the proposal of the "Tropical Forest Forever" fund as a mechanism for conserving the world's tropical rainforests. Moreover, in modelled scenarios, Brazil is assumed to have a prominent role in the carbon dioxide removal space. Numerous scenarios have pointed to Brazil as having one of the largest land-based mitigation potentials to reach the Paris targets (Griscom et al., 2020; Roe et al., 2021; Yuwono et al., 2023). BECCS (and CCS) also have a prominent role in both global and national mitigation scenarios produced with Integrated Assessment models (CEBRI, 2023; Köberle et al., 2022, 2020; Schaeffer et al., 2020). Although not a central focus of my research, it is also worth noting that Brazil is also part of the handful of countries in the world with research infrastructure that contributes to global Integrated Assessment modelling efforts.

Case I: Accelerated land-use change in the Cerrado tropical Savanna.

A prevalent concern around mitigation scenarios revolves around the role of land in mitigation and carbon removal efforts, and the potential implications of large-scale land use change for ecosystems and people on the ground. Transitioning from an abstract global discussion to an empirical space while studying a phenomenon that is yet to materialize poses a challenge for research. To address this issue, I followed Buck's (2016) recommendation to use an analogue, or proxy case study to explore the potential real-world impacts of large-scale CDR methods.

Buck suggests that: "Social science fieldwork and case studies of land use change, agricultural and energy system change, and technology adoption and diffusion can help in both anticipating the social implications of emerging negative emissions technologies and understanding the factors that shape trajectories of technological development." (Buck, 2016, p.157). Thus, proxy case studies can shed light on the social, ecological, political, and material dynamics on the ground; as well as broader questions of equity and justice, that are largely neglected in global assessments.

To identify a specific site for my study that later turned into Paper II, I adopt what I would like to call 'an eagle-eye approach', signifying a descent from the global gaze of the models to a specific geographical site frequently highlighted in global scenarios for its significant potential for land-based mitigation methods: the Cerrado Tropical Savanna in Brazil (Figure 1) (Fuhrman et al., 2019; Hurtt et al., 2020; Köberle et al., 2022). Hence, aiming to draw parallels on the potential impacts and consequences of rapid land-use transformation for CDR on local people, ecosystems, and land tenure structures, I examine the dynamics of accelerated land-use change in the Brazilian Cerrado as a heuristic.

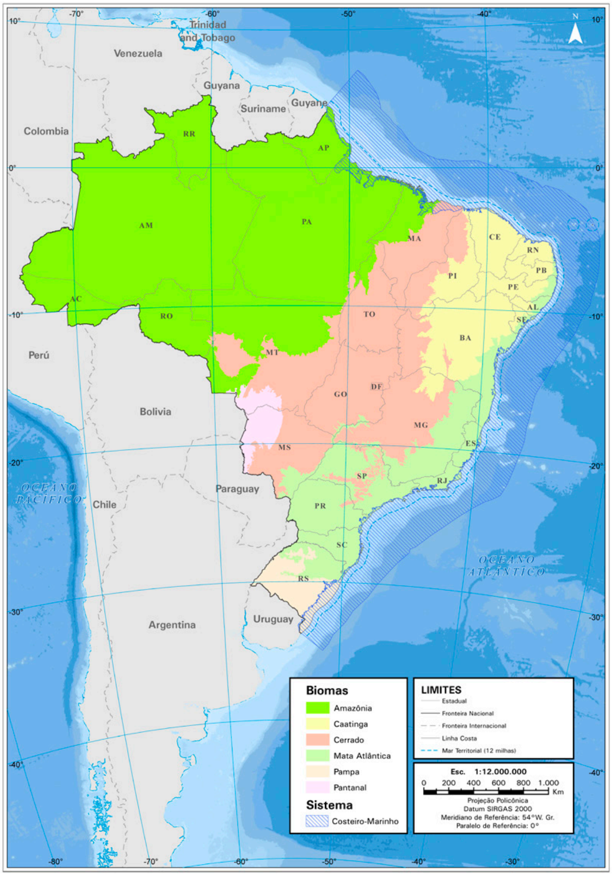

Figure 1 Map of the Brazilian Biomes (IBGE, 2019)

The Cerrado is the world's largest tropical savanna. It covers approximately 24% of the Brazilian territory. The Cerrado is also the most biodiverse savanna in the world, a global biodiversity hotspot with unique plant and vertebrate species. It is often described as the water tank of Brazil, as it hosts 8 of the 12 hydrological regions, including the second largest groundwater reservoir globally, the Guarani Aquifer. It is also described as an inverted forest due to the significant carbon reservoirs stored in its soils and the long roots of its flora (Lahsen et al., 2016).

Despite this ecological and social importance, the Cerrado savanna faces severe threats. 50% of its original vegetation has already been lost to commodity crop monocultures, and the rest is highly fragmented (Strassburg et al., 2017). Agro-industrial transformation in the Cerrado has been extremely rapid. Only between 2000 and 2015, agro-industrial activities grew 87% in the Cerrado, contributing to 60% of Brazil's annual crop output, such as soybeans, maize, and cotton. Land concentration is also much larger than in the rest of the country and land and resource conflicts are a daily experience for Indigenous and local communities. To illustrate this, official data from the National Institute of Spatial Research (INPE) show that while deforestation fell by around 50% in the legal Amazon in 2023 thanks to stricter controls and law enforcement under the new Lula government, it increased by 43% in the Cerrado. The reasons for this stark difference are explored in depth in Paper II.

For this case study, I apply a deductive approach to organize and examine the data in alignment with the analytical framework and research questions (Johansson, 2007; Reichertz, 2014). Some level of induction is also necessary to make sense of a future phenomenon –the impacts of CDR deployment – based on data from the existing issue of accelerated land-use change. Through the concept of socio-technical imaginaries, I draw parallels from past and present (emerging) visions of the future around accelerated land transformation. Through documents and interviews, I dive into a historical analysis of the societal and technological practices shaping land-use change. This allows me to examine the dynamics of knowledge co-production concerning accelerated land use change and its interaction with the materialities and historical dynamics of the area.

Data collection for this research consisted of 15 semi-structured interviews and document analysis. Semi-structured interviews are appropriate to explore complex societal issues (Dunn, 2000). Interviewees were selected by identifying key experts working on the topics relevant to the research in the Cerrado, and then through snowballing based on recommendations from the initial pool of informants. Through semi-structured interviews with open-ended questions, participants were encouraged to share insights and experiences related to their area of work and expertise relevant for this study. Topics of discussion included: climate policy, land use change, land rights, environmental legislation, agro-industrial development, deforestation, conservation, and restoration, with limited explicit discussions on carbon removal.

A key advantage of semi-structured interviews is that they facilitate focused discussions while allowing the interviewer the flexibility to explore relevant ideas that may come up during the interview (Kvale, 2007; Young et al., 2018). To ensure the reliability, consistency, and accuracy of both the research process and the subsequent outcomes, I follow certain quality criteria and good research practices (Tracy, 2019; Tracy and Hinrichs, 2017), by continually checking, questioning and theoretically interpreting the data (Kvale, 2007), through a process of crystallization (Ellingson, 2008). Crystallization involves the inclusion of multiple sources of evidence and data points (Ellingson, 2008; Tracy, 2019). Thus, after an initial content analysis of the interviews, data was contrasted, complemented, and validated with the analysis of additional documents.

Documents analysed include: national legislation, local environmental and land-use policy and grey literature from local civil society and community-based organizations documenting socio-environmental and land-use conflicts relevant to the geographic area and research scope. This effort was also complemented by a field visit to the Cerrado tropical Savanna around Brasilia.

Case II: CCS policy for BECCS and climate change mitigation

Novel carbon removal methods – like BECCS – are not just technological artefacts to be deployed, but rather, they are shaped by societal choices. CCS in mitigation scenarios is a pivotal technology for emissions reductions and a strategic part of carbon removal techniques (like BECCS and DAC) to reach the Paris Goals. Numerous cost-efficient scenarios produced through IAMs have highlighted the techno-economic potential of BECCs in Brazil (CEBRI, 2023; Garcia et al., 2022; Köberle et al., 2020). The country already has a well-established bioenergy industry and early indications of considerable potential for accommodating large-scale carbon storage capacity (Moreira et al., 2016) and Brazil has been using carbon capture technology for Enhanced Recovery (i.e. to produce more oil) for over a decade.

Carbon Capture and Storage (CCS) has three main steps. First, CO_2 is captured directly at the source during industrial processes (i.e. natural-gas-fired power plants, bioenergy plants, steel mills, cement plants, and refineries). Next, the captured CO_2 is compressed for transportation via pipelines or ships. Finally, it is injected deep into a rock formation where it is expected to remain permanently (Global CCS Institute, n.d.). The potential of CCS for climate mitigation lies not only in its possibility to avoid (some) energy and industrial-related CO_2 emissions, but also in its potential to achieve negative emissions (IEA, 2021; IPCC, 2018b).

In the early 2000s, Brazil vehemently opposed the inclusion of CCS in the Clean Development Mechanism (CDM) of the Kyoto Protocol (de Coninck, 2008). This opposition likely stemmed from a combination of environmental, technological, and strategic considerations. Concerns raised included: i) that CCS was not aligned with the principles of the CDM because it perpetuated coal or oil dependency and could redirect investments away from energy transitions, and ii) that there was a lack of technological maturity and understanding of the associated social and environmental impacts, such as leakage. Additionally, some viewed this opposition as a political negotiation strategy to prioritize other types of projects more closely aligned with the country's development priorities at the time (de Coninck, 2008; Günel, 2012).

Howeber, in recent years, after the Paris Agreement and with the mainstreaming of CCS for BECCS (and other industrial processes) in mitigation pathways, CCS has become an increasingly important point of consideration in Brazilian climate policy. In 2022, Brazil became one of the first Global South countries to introduce legislation aimed at regulating the use of Carbon Capture and Storage (CCS) for climate change mitigation (Senado Federal, 2022a). The emergence of this legislation marked the point of departure for the study of the uptake of CCS – and BECCS – into policy.

To dive into the technological aspect of CDR, I explore the emergence of CCS policy for climate change mitigation in Brazil. In doing so, I examine the political dimensions of technology and how knowledge emerging on a global scale translates into practice. We show how this process of translation can involve numerous justice concerns and material implications on the ground. Findings from this analysis were contextualized through a two-country comparative case study (Brazil-Norway) in Paper III. The comparison between Brazil and Norway provided a fruitful space for analysis for several reasons: i) Both countries have had a proactive role in advancing CCS policy – and infrastructure – in their respective regions; ii) they are both major oil produces and envision a prominent role for fossil fuel infrastructure in the long-term; iii) as Global North – Global South countries, they are representative of the types of claims and concerns that might emerge as the issue moves forward. The comparative analysis between the two countries is also pivotal for contrasting and validating the findings from the data and establishing resonance. I mainly focus on the Brazilian case here, while details about the Norwegian case can be found in Paper III.

Thematic document analysis is the main method of inquiry used in this analysis (Clarke and Braun, 2017). Thematic analysis is a method used for identifying and analysing key themes in the data based on the research question (Braun and Clarke, 2006; Byrne, 2022). This method allows us to identify emerging patterns and trends arising from the data (CCS-related policy) in relation to equity and justice. Namely, Paper III offers an assessment of how equity and justice claims are mobilized (and instrumentalized) by each of these countries to justify the advancement of CCS policy for climate change mitigation towards specific directions. In Paper III the findings are organized and presented under three broad equity concerns: i) sustainable development; ii) responsibility and capacity; and iii) vulnerability protection. In the international climate governance regime, efforts to combat climate change have been guided under these three extremely broad – and ambiguously defined equity principles (Dooley et al., 2021). The choice to organize the paper into these three broad subjects was deliberate and allowed for an in-depth examination of how justice claims are instrumentalized for CCS, in the context of broader climate policy.

Documents analysed in Brazil included: draft legislation text, transcripts of congressional debates during the process of approving the legislation, reports from government agencies, media reports with statements from the key stakeholders involved in this process (22 in total). All documents were originally written in Portuguese. The excerpts and quotes used in the paper and in this kappa were translated into English by myself, to the best of my ability. I also carried out 8

Interviews with policy makers and stakeholders involved in CCS legislation in Brazil for this research. These interviews contributed to gaining a deeper understating and knowledge of the Brazilian climate policy space but were not used as data to write the article. For the specific case of CCS (and BECCS), most stakeholders came from the energy, fossil fuel and bioethanol sectors. Although this legislation is specifically oriented towards regulating CCS as a climate change mitigation technology, the absence of climate change and environmental policy experts from other government branches, academia, and civil society should be noted (e.g. Senado Federal, 2022b).

Situating the research

Recognizing that knowledge production is 'situated' (Haraway, 1988), facilitates a critical examination of the effects generated by specific ways of knowing and the societal interest these reflect. Every researcher has an opinion, an array of lived experiences and a worldview. A researcher's background and belief system affect the way they interact, interpret, and relate to the world, and therefore the way they may approach and conduct research (Tracy, 2019). A key aspect of scientific inquiry should be – at the very least – to acknowledge the particular location of the researcher with its inherent prejudices, practices and blind spots (Haraway, 1988; Harding, 1986).

Therefore, I seek to actively acknowledge how my research practice is mediated by my own position in society. I situate myself as a woman and a PhD researcher, born, raised, and educated in the capital city of Ecuador, Quito. I then had the privilege to conduct post-graduate education at European Universities. I believe that my place of origin and my lived experience have given me a distinct perspective on justice and equity concerning global economic (and academic) relations, which have significantly influenced my research interests. In a sense, I embrace Gloria Anzaldúa's (1987) conception of border thinking as a personal experience of living and researching on the borders: at the crossroads of different social, cultural, linguistic and material boundaries. I see the journey of my research as a manifestation of this border thinking, by the ways in which my interests and research questions emerged (from an initially ontological concern), but my choices of theories and methods continue to reflect the predominantly Western (European) education system that I have lived in and that shaped my way of seeing and being in the world.

Research journey

In my research process, I follow the development of the rapidly evolving debate on negative emissions technologies (NETs) or carbon dioxide removal (CDR), with fast-moving priorities, framings, and new research gaps. From their emergence in models and the definitional politics of what is and is not geoengineering (Möller, 2019; Oomen, 2021; Talberg et al., 2018; The Royal Society, 2009), to the "reluctant acceptance" (Haikola et al., 2019a) and progressive normalization and dependence of CDR methods in net-zero framings (Jacobs et al., 2023).

My PhD position is part of the research project "Negative emissions and the politics of a projected future" financed by FORMAS, a Swedish government research council for sustainable development. The project framing served as the starting point for my research, orienting me towards examining of the role of Integrated Assessment Modelling in climate change mitigation efforts, when I didn't know where to start. Then, the fast changes in the field, in combination with the disruptions produced by the COVID-19 pandemic took me through a dynamic research journey and the need to adapt to uncertain and fast-moving circumstances. The disruptions resulting from the COVID-19 pandemic also informed the methods and data collection for Papers II and III. An iterative approach to research was crucial to reflexively refine the research process in this fast-moving space, while encountering the numerous structural and methodological limitations imposed by the disruption of the COVID-19 pandemic. I opted to focus on a single geographical area (Brazil) for my research and ultimately Papers II and III, which allowed me to bring an empirical contribution to the debate.

Initially, I had planned to write a compilation thesis of four papers using different qualitative methods including: document analysis, semi-structured interviews or surveys and participant observation in different expert meetings to study the evolution of the CDR debate and the north-south epistemic power imbalance in spaces where climate science and policy converge. The total or partial restrictions imposed during the 2+ years of the COVID-19 pandemic altered these plans substantially and forced me to reconsider the methods planned for data collection for papers II and III as most of the meetings and conferences where on-site interviews and observations could have taken place were cancelled, postponed, or done digitally – with limited access – during most of 2020, 2021.

In 2022, considering the time limitations to carry out data collection during a lengthy and scattered period, I had to rethink my methodological approach and empirical data collection. I chose to focus on Brazil as a case study, to geographically situate my research. This also allowed me to set the boundaries of my data collection during a limited period. However, it required me to establish new contacts and logistical arrangements, in addition to the need to rethink the scope of each paper. I carried out a three-month fieldwork and research stay in Brazil between November 2022 and January 2023 – already in the fourth year of my PhD. I was hosted by Prof.

Mercedes Bustamante at the Ecology Department in the University of Brasilia during most of that time. This interaction facilitated connections with leading stakeholders working in the Cerrado biome – area of study for Paper II – and allowed me to learn and experience the uniqueness of the Cerrado biome. An initial proposal for a bill to legislate CCS in Brazil was presented to the Senate during my visit, so I was able to follow this initial process closely. I also managed to connect with relevant stakeholders involved in this process and to obtain key insights of the emergent policy of CCS for climate change mitigation (that fed into Paper III). I also gained access to several sources and documents that then contributed to the document analysis for the two papers.

Ethical considerations

Activities for this research were conducted mostly in Sweden and to a lesser extent in Brazil (data collection and processing for Papers II and III). The research followed ethics and good research practice guidelines, as well as legal requirements applicable in both countries. The research was not subject to ethical review and permission in Brazil or Sweden as it did not involve the collection of personal sensitive data, nor did it entail any obvious physical or mental risks to research participants.

In addition, interview data was collected and processed in Brazil. Interviewees were informed about the purpose of the interview and the scope of the research. Consent was requested upon contact and re-confirmed at the start of each interview. No sensitive or personal information was requested or collected. Interviews were recorded on a digital recording device without internet access. Interviews were carried out in Portuguese and pseudonymized, translated and transcribed by me.

Findings

In the previous sections, I presented the context, theoretical foundations, and the analytical and methodological approaches of the research. This study was based on a collection of three papers, each one designed to primarily address a specific research question. However, they all contribute to the other two questions, to varying degrees, and to ultimately fulfil the overall aim of this research. In this chapter, I summarize the findings of the papers based on the three research questions and expand on some of the key arguments.

Justice in modelled scenarios: The devil is in the details

In this thesis, I first ask how justice concerns emerge in global, policy-relevant mitigation scenarios. Justice and equity are ubiquitous in discussions on the impacts of and responses to climate change. Equity is central to the UNFCCC and the Paris Agreement. At both, local and national levels, considerations of justice and equity frequently inform the design of climate policies, as shown in Paper III. However, the understandings (Table 2) and implementation of equity approaches in the climate governance regime remain contested (Heyward, 2007; Lefstad and Paavola, 2023). Several lines of research, despite aspiring to be policy-relevant, have consistently avoided explicitly dealing with justice and equity considerations (Klinsky et al., 2017).

A fundamental aspect of the politics of knowledge I examine is the recognition that global scenarios and cost efficiency assessments, as well as the use of large datasets, algorithms, and mathematical models, entail numerous value-laden assumptions and normativities that are seldomly made explicit, and rather presented under assertions of value neutrality, global scope, and policy relevance. As noted earlier, justice considerations are not an explicit concern in IAMs. Therefore, an examination of the critiques surrounding IAMs offers an entry point to delve into the “black box” of models and to examine what (and how) justice and equity concerns are subsumed under the models’ assumptions, structures, and methods and how these considerations contribute to the produced mitigation pathways and scenarios. This is the primary objective of Paper I.

From a three-dimensional justice lens, the analysis highlights that models embed and perpetuate narrow conceptualizations of distributive justice that cannot always accommodate questions of recognition (Paper II) – that then also affect procedure – and can contribute to perpetuating several layers of injustice when translated into policy recommendations (Paper III).

The craft of modelling

A central element of examining the politics of knowledge production is to explore how, where and by whom knowledge is generated and disseminated. By looking at the practices in climate change mitigation modelling, the review shows how the positivist paradigm guiding IAMs in conjunction with their large aggregate datasets and algorithmic complexity give rise to a seemingly unsituated, and therefore globally relevant view on how to best mitigate climate change.

The analysis in Paper I suggests that this perceived universality in modelling efforts leads to forms of exclusion and exclusiveness not only across disciplines, but also across geographies and worldviews. As noted earlier, literature on the patterns of authorship in the IPCC has shown that this self-proclaimed policy-relevant research is produced by a small epistemic community in a handful of Global North countries with overrepresented disciplines, i.e., natural sciences and economics (Corbera et al., 2016; Hughes and Paterson, 2017)[1], and ultimately replicate modellers' preferences and societal values (Ellenbeck and Lilliestam, 2019). This has clear recognitional and representational justice implications in the way modelling is done and whose voices get to be heard in the process; while distributional concerns manifest in the "grandfathered" (Table 2) way energy use and economic growth are projected in global scenarios (Hickel and Slamersak, 2022).

Part of the strategic role of IAMs results from the ability of modellers to both respond to societal demands and craft responses, while also aiding policymakers in formulating new goals (Lövbrand, 2011; van Beek et al., 2020). Based on the almost exclusive representation of the Global North in modelling efforts, one could infer that the societal demands being considered in this process follow a similar pattern. As an example, concerns about the biases that unfairness and growing Global North-South inequality embedded in modelled mitigation assessments have been raised since the earlier days of modelling (Parikh, 1992), yet they prevail in policy-relevant scenarios to this day (see also Bluwstein and Cavanagh, 2023; Hickel and Slamersak, 2022; Kanitkar et al., 2024). Thus, our review provides a glimpse into the question of who gets to speak for the future and whose voices are effectively

[1] Brazil is one of the exceptions. The IAMs developed in Brazil are based on the Austrian model from the International Institute for Applied Systems Analysis (IIASA) and grounded on the same epistemological and methodological foundations.

being considered in the quest to make science for policy. CDR research follows a similar pattern (Sovacool, 2023).

The narrow frames of economic modelling

Policy design relies on economic models for legitimacy. Economics deals with the allocation of resources in society. Findings in Paper I (and indirectly in Paper II) point to the political nature of economics. The review shows that models rely on a narrow set of neoclassical economic parameters to evaluate the most cost-efficient ways to reach the Paris targets of 2°C, as a way to avoid entering the political realm, and without considering the normativities embedded in economic framings (Keen, 2020). As part of this Thesis work, I outline how the unexamined cost-efficiency considerations of contemporary IAMs insinuate the placement of land-based CDR in the Global South, where land and labour are cheaper, with inadequate assessment of the impacts this might have on vulnerable people and ecosystems (Paper II).

The study of the economy as a whole (macroeconomics) has been largely dominated by neoclassical economic thought. Neoclassical economics has been the basis of much of the economic research and policy analysis for much of the 20th and 21st centuries. It is, therefore, not surprising to see this epistemic privilege prevailing in modelling efforts intended to inform policy. The problem arises when the illusion of objectivity, universality and value neutrality entrenched in quantification methods and algorithmic results conceal the inherently normative assumptions embedded in economic parameters and other choices made in model construction. Accordingly, contemporary climate change mitigation models depoliticize a fundamentally political question. The review in Paper I notes that this is evident for numerous scholarly critiques. Some explicitly point to the normative issues of economic parameters (Asefi-Najafabady et al., 2020; Keen, 2020; Stanton, 2011; Stanton et al., 2009), while other debates remained within the bounds of neoclassical economic thought but explicitly debated the normative dimensions of it (e.g., discount rates) (Dasgupta, 2008; Emmerling et al., 2019; Stern, 2006).

By critically scrutinizing key foundational assumptions in the economics of the models, my analysis in Paper I underscores the imperative of understanding the limitations and normativities inherent in mainstream economic thought when informing decision-making processes. The analysis suggests that notions of utility maximization, rational choice, or general equilibrium are not aligned with real-world economic conditions and can only offer limited insights into the creation of decades-long scenarios in a world with an increasingly unstable climate and political system. Further, the narrow focus on market mechanisms inherent in this discipline (i) often neglects important social and environmental considerations – issues that are at the core of climate change – or (ii), is contingent on, e.g., maintaining inequitable rates of income distribution across regions in the long term to reach temperature targets. This can lead to fundamentally flawed policy recommendations

(Paper III) with detrimental effects on vulnerable populations and local ecosystems (Paper II). These findings also speak to a larger debate on the need for pluralist approaches in research that intends to be policy-relevant, policy design and the economics.

The analysis of the accelerated land-use change in the Cerrado (Paper II) contributes to this debate by analysing the political uses of notions of marginal land, a concept originating from David Ricardo's 19th century's theory of rent to assess the productivity of land. Findings in both papers point to the inherently political nature of economic thought (Callon, 2007; Nelson, 2008), which is often masked under its mathematical models and deep-rooted disciplinary assumptions.

Technology in models

Findings of the review show that examining expectations of cost-effective technological innovations in models is crucial, as they mirror historical trends and politics of resource use and extraction between the Global North and South. The reliance on CDR in models results from economic optimization rather than a comprehensive assessment of technical, environmental, political, and social factors. High discount rates, narratives of techno-economic incrementalism (McLaren and Markusson, 2020), the logic of markets, and feasibility within model structures make BECCS and Afforestation appear cost-effective in long-term mitigation pathways. My analysis in Paper I also shows that technological representations in models perform an important political role in shaping current policy choices, by influencing expectations and funding priorities. Therefore, they entail a series of justice and equity considerations which are empirically explored in Paper III, as well as in the last subsection of this chapter.

With regards to the socio-ecological interactions and planetary limits, a common critique in the literature is that the deployment of land-intensive CDR, like BECCS and Afforestation/Reforestation, can impact biodiversity, water availability, food security, and livelihoods, disproportionately affecting vulnerable countries (Dooley and Kartha, 2018; Fuss et al., 2018; McElwee, 2022; Smith et al., 2016). Thus, IAMs' least-cost distributions may add more burden on historically affected countries, communities, and Indigenous populations. Further, scaling up CDR through market logics and governance mechanisms may exacerbate the challenges faced by communities dealing with climate change, resource extraction, and land rights, reinforcing systemic marginalization, as I demonstrate in Paper II.

Ultimately, our analysis in Paper I points to the importance of not only diversifying models and scenario-making efforts outside the bounds of IAMs, but also focusing on epistemic and cognitive justice, as a fundamental step to strive for more diverse, equitable and inclusive policy options and climate futures.

Land for Carbon: Whose Land and Whose Carbon?

The second research question of my thesis inquires about the socio-ecological, material, and political dynamics that large-scale CDR deployment could replicate. An important point of controversy from mitigation scenarios is the unrealistic land requirements that scenarios deem technically feasible. Global mitigation scenarios – and recent net-zero plans (Dooley et al., 2022; Smith et al., 2022) – assume unprecedented scales of land-use change for A/R and BECCS, and anticipate the deployment of these methods in the Global South (Griscom et al., 2020; Jaschke and Biermann, 2022; Smith et al., 2016).

Studies aiming to incorporate more realistic constraints into the models have looked into marginal lands for CDR deployment to reduce land-use competition (Fajardy and Dowell, 2017), while others have looked into recent historical experiences of land use change –namely, the expansion of soy and palm oil-, in an effort to incorporate a broader range of technical, socio-political and economic considerations into the set of assumptions on land-use change for CDR in models (Doelman et al., 2020; Perkins et al., 2023; Turner et al., 2018).

The examination of such historic and ongoing events as proxy case studies (Buck, 2016) can provide empirical insight into the effects of large scale land use change on the social, ecological, political, and material dynamics and justice concerns on the ground. Comparable effects are expectable from but largely neglected in the construction of global mitigation scenarios employing land-based CDR at scale. This can also bring attention to the justice concerns that may arise from global assessments, the visions of the future they create, and the political uses or agendas they may tacitly – or explicitly – support. In Paper II, I argue that global assessments of large-scale land availability risk being translated into new local imaginaries of climate change mitigation. These imaginaries could inadvertently perpetuate previous problematic framings and erasures concerning the use, value – and ownership – of land, while also exacerbating existing conflicts on the ground.

Marginal lands

As a foundation to this study, I critically assess the concept of 'marginal lands' which are considered preferable sites available for land-based CDR. Specifically, I analyse its definitions, historic origins, its relation to tropical savannas and existing, conflicting uses or roles in critical local ecosystems. I examine these definitions under the premise that interpretations of nature as an analytical category are influenced by a range of factors, from cultural and historical perceptions, to human-made categories, classifications and specific research methods (Latour, 1999, 1993). Once established, these are difficult to change (Turnhout, 2018), and elicit specific material and political effects (Lövbrand et al., 2015).

Efforts to address debates on land-use change often employ the concept of marginal land to assess global cost-efficiency and to avoid competition with food production and other land uses (Cai et al., 2011; Fajardy and Dowell, 2017; Khanna et al., 2021). The idea of marginal land has its roots in 19th century agricultural economics (Ricardo, 1817). It emerged as a concept to describe areas that were less suitable for traditional agriculture and thus considered 'unproductive'. Over time the concept evolved to include other considerations and has been used by different disciplines concerning land use planning and environmental management. The expansive use of this concept has resulted in a broad spectrum of definitions (Khanna et al., 2021; Nalepa, 2013; Shortall, 2013) (Also see Paper II for examples).

Studies have shown that notions of what constitutes marginal lands are subjective, value-laden, and subject to implicit biases and in some cases may be used for political purposes (Borras Jr and Franco, 2013; Nalepa and Bauer, 2012). A critical concern about the political uses of the concept of marginal land is that it supports readings of a landscape aimed at controlling resources and improving economic productivity– but disregards the ways in which communities face dislocation (Ariza-Montobbio et al., 2010; Makki, 2018; Singh, 2022). A further risk of using the concept of marginal lands lies in that it can be used to mis-categorize critical ecosystems as marginal/unproductive areas available for human occupation to render them economically productive, like e.g. tropical savannas (see Box 1) and – until recently – forests. Identifying the impact of 'marginal land' definitions is particularly challenging when it comes as an additional parameter in studies with large datasets (Robbins, 2003; Robbins and Maddock, 2000), as is the case with IAMs, due to the complexity and aggregation of variables, parameters and assumptions, as shown in our analysis in Paper I.

In climate change mitigation research, the definitional ambiguity of marginal land lacks thorough examination, especially in the context of future CDR (Buck, 2016). Calculations of future scenarios are frequently based on borrowing definitions of marginal land from existing studies, with little or no further clarification. This might result in outcomes that motivate new local land-use change for global climate change mitigation, posing risks to critical local ecosystems (see Box 1), and marginalized traditional populations with insecure land tenure (McElwee, 2022).

Box 1. Tropical Savannas

Tropical savannas were once thought to be the outcome of land degradation due to anthropogenic uses or deforested tropical forests (Parr et al., 2014; Veldman et al., 2015a). However, over time a growing body of research has shown that tropical savannas are not degraded forests but rather unique and much more ancient ecosystems with their own ecological significance and characteristics, with important biodiversity and charismatic fauna (IPBES, 2019). They play a crucial role in water supply and food security, store substantial amounts of carbon below ground and are critical to global biodiversity and ecosystem health (Beerling and Osborne, 2006; Bond and Parr, 2010; Murphy et al., 2016). Savannas are also home to a large array of culturally diverse Indigenous, traditional, and local communities (Fairhead and Leach, 1996; ISPN, 2022). Yet, due to this historical misconception, savanna ecosystems have been largely overlooked by nations and the international community, understudied by science (Parr et al., 2014); and even labelled as 'marginal lands' by the agricultural and soil sciences (Schuh, 2001; Thomas et al., 1999; Toledo and Nores, 1986).

The case of the Cerrado shows how scientifically informed definitions of marginal lands and categorizations of an ecosystem (e.g., tropical savannas) can interact with localized historical, political, socio-ecological, and economic dynamics and get ingrained in the emergence of specific national sociotechnical imaginaries.

Over the past 50 years, the Cerrado has seen significant accelerated land-use change for soybean production (Lahsen et al., 2016; Strassburg et al., 2017). Like many other non-forest ecosystems, the Cerrado is still (mis)identified in scenarios and other land availability assessments as potential area for forest cover expansion (i.e., Afforestation) and bioenergy crop production (Abreu et al., 2017; Lewis et al., 2019; Veldman et al., 2015b, 2015c; Zomer et al., 2008). In Paper II, I show how assessments of marginal lands, co-produced in a close interaction between social and scientific categorization of an ecosystem (e.g. Schuh, 2001; Toledo and Nores, 1986) can be adapted for political purposes feeding into specific sociotechnical imaginaries and nation-building efforts. I argue that the events observed in the recent transformation of the Cerrado provide a window into the ramifications expectable from the large-scale implementation of CDR, as outlined by global mitigation scenarios.

A changing landscape: Ghosts of the Cerrado's past, present, and future

It was mainly through land use conversion of the Cerrado that Brazil became a major global producer of soybeans, maize, cotton, and beef (Lahsen et al., 2016). In Paper II, my analysis demonstrates how the transformation of the Cerrado was facilitated by authoritative narratives portraying the area as marginal or uninhabited, ideas of development driven by agricultural modernization, and national techno-scientific achievements. I trace back these scientifically informed visions of agricultural modernization and marginality to the Green Revolution (Nepstad and Stickler, 2008; WFP, 2006), when the creation of new soy varieties adapted to the Cerrado marked a turning point for agro-industrial modernization (Crocomo and Spehar, 1981). In addition, in this Paper, I show how complementary land governance mechanisms for environmental conservation (i.e., the Brazilian Forest Code) implemented under these conditions may inadvertently come to the detriment of local populations and ecosystems deemed less valuable. Moreover, at the core of all these efforts, tensions emerge under promises of progress, wealth, and development that, at least for local populations, often fail to materialise. Instead, these efforts serve as sites of exclusion and marginalization of context-specific knowledge, practices, and ways of living.

Using this case heuristic to examine the translation of abstract global knowledge into material realities on the ground, my analysis reveals the practical implications and potentially profound changes in the socio-ecological relations that visions of accelerated land use change for CDR could entail. I show how imaginaries of BECCS and Afforestation would not only exacerbate stresses on land rights and biodiversity loss, legitimized under claims of global mitigation and CDR efforts, but would also put pressure on other resource use, and exacerbate the latent and often violent socio-environmental conflicts. Many of these conflicts are already being aggravated by changes in local temperatures (Rodrigues et al., 2022), precipitation patterns and river flows (Salmona et al., 2023) due to climate change, agricultural intensification and forestry plantations in the Cerrado (Ferraz et al., 2019; Veldman et al., 2015b, 2015c).

A critical concern regarding these findings is that, nowadays, studies driven by expectations of land use change continue to overestimate A/R potentials and misidentify non-forest biomes as suitable areas for forest cover expansion or bioenergy crop production. Such studies often neglect the problematic historical and systemic erasures embedded in these assessments (Abreu et al., 2017; Bond et al., 2019; Fernandes et al., 2016; Gerber, 2011). As a parallel example to this, a study from 2019 calculating the global tree restoration potential, estimated a sequestration potential of 205 Gigatons of Carbon (Bastin et al., 2019). Subsequent analyses showed that this estimate was overstated by about 5 times (Lewis et al., 2019; Veldman et al., 2019). Part of this inflated estimation was due to the study including trees in non-forest ecosystems, like savannas and grasslands.

In addition to the ecological simplification of tree planting in non-forest ecosystems and the disregard for biodiversity in these areas, these highly aggregate studies offer no insight into the existing land uses and communities inhabiting areas identified for carbon sequestration. Consequently, by ignoring present land uses, the complexities of existing land tenure structures, conflicts, and governance dynamics, these top-down assessments might convey a dangerous message by i) setting unrealistic targets, ii) exacerbating erasures, and iii) contributing to justifying unjust land governance practices (Fleischman et al., 2022). In policy processes, such policy-relevant knowledge might be invoked as evidence to advance specific interests and political agendas. Indirectly, studies of this nature may also contribute to further replicating ideas of empty or abandoned lands and serve as excuses or justifications for further land grabs legitimized under the flag of global mitigation efforts, as Paper II shows. Box 2 provides another example of how scientifically informed global environmental policy efforts continue to overlook non-forest ecosystems, like the Cerrado.

Box 2. Deforestation free productions: navigating definitional challenges

A recent example of how valuable ecosystems are systematically marginalized through simplified, but politically motivated categorizations was elicited by discussions around a recently approved EU legislation prohibiting the import of goods linked to deforestation (European Commission, 2022), at the end of 2022. The EU used the FAO's technical definition of forest in its legislation to limit which type of deforestation would not be accepted for commodity imports: "land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10%, or trees able to reach these thresholds in situ" (FAO, 2020). While it signified an important step to tackle new deforestation, this definition excludes all other ecosystems with different characteristics. Experts, activists and researchers have warned of the dangers of indirect land use changes in other biomes that these omissions can create, as previous experiences have already demonstrated (Gibbs et al., 2015).

As one interviewee working on conservation noted: *"...it leaves out a big set of kinds of vegetation that are not forest but that are still critical ecosystems, maybe even more important than some forest, in terms of carbon. In the Cerrado, we find wetlands that are even bigger carbon sinks than forests. So, it's a definition aiming to make things easier, but it does not reach the goal that it is trying to set, for instance, of emissions reduction."*

Using the definition of Forests from the FAO, some argue, was a "*motivated decision*", as existing data shows that most deforestation for commodity production in Brazil happens in the Cerrado. Between 1985 and 2020, the agricultural area in the Cerrado grew by 464% (Mapbiomas, 2021). "The EU is not accepting to buy commodities associated with deforestation of forests, but when deforestation is associated with savannas or grasslands, there seems to be no problem. […] Who can decide, and based on what criteria, which biome can die, and which biome survives?"

This encapsulates how, as forest preservation and reforestation efforts regain impetus in climate policy, new risks emerge for other non-forest ecosystems that do not fit into specific definitional categories.

Findings in Paper II also demonstrate how scientific claims can feed future visions and policy efforts, leading to top-down, simplified readings and modes of governing the landscape with unintended consequences (Scott, 1998), and contradictory policies in favour of vested interests (c.f. Oliveira, 2013). Just as the discourse of feeding the world was used to justify land concentration, deforestation, and the widespread use of agrochemicals, decarbonization efforts can potentially elicit new waves of accumulation by dispossession and justify further inequality under the discourse of fighting the climate emergency. In Brazil new imaginaries are beginning to emerge, with claims that Brazil can become “the Saudi Arabia of the Carbon markets”(Justino, 2021), or the “Saudi Arabia of green energy” (Gallas, 2023).

However, to realize this vision, the analysis suggests that the large-scale, accelerated implementation of land-based CDR methods would demand efforts, visions, infrastructure, investments, governance, and land management mechanisms akin to those that facilitated the rapid agricultural modernization of the Cerrado. In essence, achieving scalability, measurability, and verifiability in land-based removal would demand structural configurations like those of large-scale agro-industrial modernization. This effort would further solidify the power of elites through new processes of land appropriation and wealth accumulation, thereby exacerbating existing socio-ecological conflicts on the ground.

Land tenure chaos

Most of the world’s land is still governed under traditional and customary systems (RRI, 2015). A recent study showed that scaling CDR as assumed in archetypal IPCC 1.5°C scenarios could lead to the (re)escalation of the global land rush (Bluwstein and Cavanagh, 2023). Land tenure and land rights emerged as a central concern from the empirical data in Paper II, an aspect that has also been largely overlooked in the CDR debate (McElwee, 2022), as well as in research and implementation of restoration efforts (Erbaugh et al., 2020; Fleischman et al., 2022).

In Paper II, I explain some of the historical, socioecological, and economic complexities and – often violent conflicts associated with land accumulation in the Brazilian Cerrado. While the intricacies of the case are region-specific, the arguments presented are applicable beyond this geographical context: the pervasive contestation and vulnerability of land rights remains a universal concern. Below I elaborate further on how the different treatment of land rights among Indigenous, Quilombola and Traditional Communities in the Cerrado complicates land regularization processes even further.

Land grabbing has been a prevailing issue in Brazil since colonial times and is deeply entrenched in the legislative system and supported by powerful economic interests. A recent study assessing land ownership in Brazil found that over half of the country’s lands might be subject to dispute or contested ownership claims (Sparovek et al., 2019).

Box 3. Technologies of land grabbing

Land grabbing technologies in Brazil have adapted over time

In Portuguese, the word for land grabber is "grileiro," derived from the word "grilo," or cricket in English. In the past, fraudulent land titles would be placed in a box with crickets. This process aged the documents, suggesting they had been in someone's possession for a long time. Nowadays, instead of crickets, GIS technology and property self-declaration mechanisms are some of the ways employed to perpetuate this practice.

As noted in Paper I, by overlooking, simplifying, or making assumptions about land use and governance, global, policy-relevant research may inadvertently help to legitimize historical injustices and erasures regarding the access and rights to land. In Brazil, as in most of the rest of the world, the territorial rights of Indigenous and traditional communities face persistent threats, and land governance mechanisms are often fragile and susceptible to alteration or reinterpretation.

A recent illustration of this occurred with the approval of a bill termed Marco Temporal (temporal framework) by Congress at the end of 2023, despite being previously vetoed by the president and declared unconstitutional by the Federal Supreme Court. The Brazilian constitution mandated the State to regularize all Indigenous territories within five years of its promulgation in 1988 (see Table 3). However, more than three decades later, this task remains unresolved, marked by ongoing conflicts and persistent issues of land grabbing and dispossession (AATR, 2021). According to this new Marco Temporal bill, Indigenous peoples are granted the right to claim ownership only of lands they were already occupying in 1988. This temporal framework poses a threat to the rights of numerous Indigenous communities, potentially dispossessing them of their ancestral territories if, for example, they were expelled from their lands and unable to return before 1988 (Câmara dos Deputados, 2023).

Moreover, the territorial rights of Indigenous, Quilombola and traditional communities in Brazil are recognized under different legal frameworks. The differing treatment of land rights among population groups can complicate collective efforts toward procedural justice. Table 3 provides an overview of the different legal frameworks and status of land regulations of the different population groups.

Table 3. Land tenure legislation for different population groups

POPULATIONS	LEGAL FRAMEWORK	STATUS
Indigenous: Indigenous peoples are those who, having historical continuity with pre-Columbian groups (i.e. before European colonization), consider themselves distinct from national society. Indigenous people are those who recognize themselves as belonging to one of these communities and who are recognized by them as one of their members. (Presidência da República, 2022)	Ancestral right to land recognized in the constitution of 1988: Article 231 acknowledges the ancestral land rights of Indigenous populations. It recognizes their social organization, customs, languages, beliefs, and traditions, along with their original rights over the lands they traditionally occupy. The process of recognition and land regularization is rooted in self-determination. After territories are regularized, the land remains publicly owned.	775 at different stages of the demarcation process (ISA, 2024): 142 – in the process of identification 46 – identified (with study report approved) 66 – declared by the Ministry of Justice 4521 – Homologated / regularized
Quilombola: Officially defined as ethnic-racial groups, determined by self-identification criteria, with distinct history, kinship and territorial ties, with a presumption of black ancestry related to resistance to the historical oppression suffered (i.e. former enslaved populations) (Presidência da República, 2003)	The rights of the Quilombola were recognized under transitional provisions (disposições transitórias) in the Constitution: ART. 68: Quilombo communities occupying their lands are recognized as having definitive ownership, and the State must issue them the respective land titles.	Only around 12% of the Quilombola peoples reside in territories with officially recognized land titles (IBGE, 2023)
Traditional communities: Officially defined as culturally differentiated groups who recognize themselves as such, who have their own forms of social organization, who occupy and use territories and natural resources as a condition for their cultural, social, religious, ancestral and economic reproduction, using knowledge, innovations and practices generated and transmitted by tradition (Presidência da República, 2007).	Not recognized from a territorial standpoint, these communities are recognized as inhabitants of Conservation Units. Legislation within the National System for Conservation Areas provides territorial protection and grants them the "real right of use," akin to a concession from the state, allowing these communities to remain in these areas. Communities are only permitted to live and use the land in areas classified as Conservation Units for Sustainable Use.	4.82% of all current Conservation Units (those classified as Sustainable Development and Extractivist reserves) (CNUC, 2024)

Interventions like large-scale A/R or biomass production (for BECCS) implemented under the same configurations as other (agro-industrial) land transformation processes, threaten to introduce another layer of conflicts on top of the existing ones. Furthermore, the historical disregard for savannas has also contributed to a lack of knowledge about the ecosystem (Parr et al., 2014). Biases in knowledge become visible and prevail later in legislation – as shown in the example from Box 2. Similarly, previous studies have noted that forest carbon-related projects, like REDD+, may inadvertently harm grasslands by encouraging the planting of trees

(Abreu et al., 2017; IPBES, 2019; Lehmann, 2010; Parr et al., 2014), if safeguards are not adequately implemented and followed.

Additionally, restoring savanna ecosystems more difficult, labour intensive and costlier than planting forests (Bond and Parr, 2010). This was noted by one of the experts working on ecosystem restoration in the Cerrado that I interviewed: "The restoration efforts we've undertaken thus far have not yielded the desired biodiversity results, primarily due to alterations in soil conditions. Therefore, restoring the Cerrado presents an extremely challenging task." With these considerations, and under notions of cost-efficiency and the tunnel vision of carbon metrics, betting for bioenergy crops of a monoculture of eucalyptus trees – as afforestation or wood for biofuels – could easily become the preferred option for profitable carbon sequestration in non-forest ecosystems.

Savannas for biofuels

During the biofuel boom, extensive debates emerged about the social, ecological and land use impacts of biofuel expansion (Cotula et al., 2008). This continues to be a contested subject and debates have been reinvigorated in recent years, with the invoked necessity of BECCS in Paris compliant scenarios. Numerous biomass alternatives exist for energy production. In recent years, wood pellets have become the leading solid biomass commodity for electricity in the global market, as its less expensive and easier to collect and transport (Brack, 2017). In Brazil, most biomass energy derives from sugarcane and corn. But, similar to trends seen elsewhere, exports of wood pellets from Brazil have been on the rise (Aldridge, 2021), a trend likely to persist to meet escalating demand, as investments in BECCS grow.

Mitigation scenarios assessed by the IPCC operated under the assumption that biomass is a carbon-neutral energy source. The carbon-neutrality of biomass is grounded on two assumptions: 1) carbon emitted during wood burning is absorbed by forest re-growth, and 2) according to international GHG accounting regulations established under the UNFCCC and the Kyoto Protocol, emissions from biomass are only accounted for in the land-use sector, not the energy sector (Brack, 2017; Ramos, 2022). However, studies have shown that, in addition to all the potential socio-ecological interactions attributed to BECCS (EASAC, 2022; IPCC, 2019), biomass energy, particularly wood-based biomass, may emit more GHGs than fossil fuels per unit of energy (Brack, 2017; NRDC, 2021; Sterman et al., 2018). This suggests that biomass-based energy might not be the best approach to energy security, efficiency, and to reach the goals of the Paris Agreement (EASAC, 2022). An issue further exacerbated by the sluggish implementation of carbon capture and storage (CCS) technology at present.

In Paper III, we empirically analyse this issue by examining the performative role of scenarios in the emergent policy context of CCS, as well as the political causes and consequences of this technology intended to support mitigation efforts.

Removing carbon: the role of Carbon Capture and Storage

In the third research question of this thesis, I inquire about the ways in which global scenarios with CDR translate into climate policy and action at the national and local levels. Since its inception in the Paris Agreement and its prominence in IPCC scenarios, the promise of BECCS has become a powerful discursive tool for decision-makers in their formulation of net-zero commitments. In addition to the land-use concerns inherent to biomass production discussed in the previous section, in Paper II (and elsewhere in the literature), the scalability of BECCS is contingent on the large-scale implementation of Carbon Capture and Storage (CCS) technology. Therefore, drawing insights from the literature on the politics of technology and equity, in Paper III, we examine the post-Paris emergence of CCS technology from the ways it is used in scenarios and contrast them with its real-world causes and consequences in policy and action. This includes an assessment of how technology is envisioned and implemented in a broader energy policy context.

The review and analysis in Paper I highlights that justice can be understood and interpreted in various ways, depending on the cultural, legal, philosophical, and political standpoint. In the global climate governance regime, divergent interpretations of justice and equity have been a longstanding subject of debate. To understand some of these divergent interpretations and their implication, in Paper III, we examine how countries envision CCS policies to support climate change mitigation action in the context of three general equity concerns: sustainable development, vulnerability and historical responsibilities and capacities. These three principles have been at the core of equity discussions in the international regime, yet they are broadly defined (Dooley et al., 2021), allowing for a certain degree of interpretative flexibility and political utility in various contexts. Our study in Paper III suggests that notions of equity are often instrumentalized under discourses of development and just transitions, and they have become effective tools to contribute to delay emissions reductions.

Viewed through the lens of the politics of knowledge, the analysis of the political aspects of CCS technology is also indicative of the hidden political dimensions that may exist within every layer of assumptions and parameters of integrated assessments. Moreover, the analysis in this paper shows how policy analysis can gain political strength when considering the technicalities of the models and methods that contribute to shaping these policies in the first place. Below I detail some of the findings for the Brazilian case.

CCS for climate change mitigation

In 2022 a new bill proposing to “regulate the exploration of the permanent storage of carbon dioxide for the public interest, in geological or temporary reservoirs, and its subsequent reuse” was introduced to the Brazilian Senate (Senado Federal, 2022a). During the first public hearing at the Senate on November 30, 2022, the Senator who introduced the bill noted that: "At the global level, CCS activity has been identified as a strategic element in several projections of transition scenarios that aim to achieve zero CO_2 net emissions targets by 2050, according to reports by the International Energy Agency and the Intergovernmental Panel on Climate Change." (Senado Federal, 2022b). This statement is a clear indication of the performative power of global mitigation scenarios and assessments (Beck and Mahony, 2018a), and the evidence-based inevitability that emerges when scenarios and pathways narrow the corridor of possibilities for climate action (Beck and Oomen, 2021). In this bill, BECCS was also evoked as a pivotal technology to make Brazil a leader in delivering negative emissions:

> In a context where the Brazilian biofuel production industry stands as a benchmark both nationally and globally, with recognized growth potential in the coming years, the prospect of combining bioenergy production with CCS (BECCS) could represent the first step towards enhancing Brazil’s competitiveness in offering products with "negative emissions". (Senado Federal, 2022, Pl. 1425/2022, pg.17)

In scenarios, different mitigation technologies (e.g. CCS, BECCS, A/R, renewables, nuclear energy) compete against each other based on cost-efficiency considerations (Tavoni and Socolow, 2013). In the real world, technological deployment responds to numerous political and socio-economic factors (Miller et al., 2013). Technologies also have political causes and consequences (Bijker, 2010; Collingridge, 1980; Winner, 1980). Consequently, regarding BECCS, CCS, and renewables merely as technological artefacts competing against other technologies in models is bound to yield unrealistic outcomes. Studies have previously pointed out that models tend to show biases towards certain technologies (see Paper I) and have consistently underestimated the deployment of renewable energy technologies (Creutzig et al., 2017).

This issue is further compounded by oversimplified carbon accounting assumptions regarding the carbon neutrality of forest biomass are included as parameters for BECCS (Norton et al., 2019), and the large energy requirements needed to capture and compress the CO_2 (Kearns et al., 2021), and other resources required to operate, such as water (Global CCS Institute, 2016; Yang et al., 2020). Furthermore, CCS globally has a history of overpromising and underdelivering. For example, a 2018 study showed that the pace of CCS deployment globally is one hundred times slower than it would be required to meet the 2°C target, with projections to 2050 capturing just 700 Mt CO2 yr−1, not the minimum 6000 Mt (or 6 Gt) CO2/yr. (Haszeldine et al., 2018). And, as noted earlier, only 0.1% of CO2 removal is attributed to technological CDR methods with CCS (Powis et al., 2023).

Findings from Paper III support the argument that CCS technology is both shaped by and reliant on specific types of politics to operate (Winner, 1980). In essence, disentangling CCS technology from the fossil fuel industry appears extremely difficult, if not practically and politically unfeasible. The technical expertise related to infrastructure, know-how, operations, as well as emerging governance mechanisms, and even financing efforts, are deeply intertwined and reliant on this industry. This dependency is evident in the analysis of Paper III, as it was in the earlier stages of CCS debates in the international climate regime (de Coninck, 2008; Günel, 2012). Therefore, the interchangeable use of CCS in models with other mitigation technologies might also indirectly contribute to masking profoundly significant political and societal choices and end up favouring fossil interests in the short term.

Energy transitions are costly and take time, and “how we build and use infrastructure shape and reflect everything from our political systems, working patterns, living arrangements, leisure practices, health outcomes, and environmental conditions” (Miller et al., 2013 p.141). The analysis in this research indicates how refusing to recognize politics that bring technological interventions to being, give them value and purpose, can feed into the illusion that we can substitute technological innovations to deal with environmental crises without addressing the underlying socio-economic systems and political relations that produce them (c.f. McLaren and Markusson, 2020). Moreover, in Paper III we show how actions, statements and policies claim to strive towards net-zero, while expanding carbon-intensive activities by explicitly relying on CCS (or CDR more broadly).

In Brazil, BECCS was evoked as a future opportunity to advance CCS legislation. At the time the bill was introduced, plans to build the first BECCS facility in the State of Mato Grosso do Sul were already in the pipeline of the bioenergy company FS Bioenergia (FS, 2023). However, upon deeper analysis of the role of CCS in relation to broader energy and just transition plans, it becomes evident that fossil infrastructure stands to benefit the most from the promise of future CCS. As scholars have previously warned (Carton et al., 2023; McLaren and Markusson, 2020), this analysis empirically shows how CCS serves a political function by not only averting stranded assets but also by facilitating and promoting new fossil infrastructure. A prime example of this is evident in the extension of the operational lifespan of highly polluting, inefficient, and largely subsidized coal plants. For instance, the Jorge Lacerda thermoelectric complex in the southern State of Santa Catarina, also the largest coal power plant in Latin America, was originally authorized to operate only until 2028. However, in 2022, through the Program for Just Energy Transitions, it was allowed to extend its operation until 2040, and to consider the use of coal with CCS beyond that date (Conselho do Programa de Transição Energética Justa, 2022).

Brazil is currently the only Latin American country with plans to build new coal energy infrastructure. This, despite the limited implementation of previously proposed thermoelectric power plants due to their high costs compared to renewable energy sources (Global Energy Monitor, 2023). The program for Sustainable Use of Mineral Coal, for example, includes investment and research for new and more efficient coal plants that could incorporate CCS technology for decarbonization purposes (MME, 2021a). Recognizing the inefficiency of retrofitting old thermoelectric plants with CCS infrastructure, this initiative prioritizes the modernization of the sector through the replacement of existing coal power plants with newer, more efficient ones with CCS, rather than orienting efforts for alternative energy sources in coal-mining regions. In other words, this current approach seems to be more aligned with re-carbonization efforts rather than facilitating a just transition.

These visions and ideals of CCS also fall into a larger imaginary of Brazil becoming "the Saudi Arabia of green energy" (Presidência da República, 2023). It is important to note, however, that CCS is only one small aspect of this vision, which includes broader, and perhaps more important initiatives like improved energy efficiency, and investment in renewables, in addition to CDR (MME, 2021b). But it also includes more fossil fuels, as Brazil aims to become the fourth largest fossil fuel producer in the world (Newsroom, 2023). In that sense, expectations of technological innovation around CCS in Brazil appear to align with energy imaginaries rooted in ambitions akin to those observed in the Cerrado (Paper II) and other related energy innovations elsewhere (Kuchler and Bridge, 2018; Singh, 2022). That is, ambitions primarily aiming at stabilizing the current fossil-fuel-driven neoliberal system. A system progressively challenged by increasing energy insecurity and agricultural stagnation exacerbated by climate change.

Just transitions, but when?

Recognizing the global imperative to transform the energy matrix in the future, Brazil consistently invokes the idea of Just Energy Transitions in its climate and energy plans (e.g. Conselho do Programa de Transição Energética Justa, 2022). This vision, however, does not seem to entail effectively moving away from using fossil fuels, but rather simply for "unabated fossil fuels", as the policy analysis in Paper III shows. So, efforts and resources that could well go into retraining workers and building alternative energy infrastructure, are instead used to perpetuate the cycle of coal and further cement this fossil-based path dependency.

In the case of coal, arguments for job and energy security are often used to justify prolonging the life of thermoelectric energy. This argument, however, brings forth several paradoxes. For instance, regarding job security, discussions often focused on the livelihoods of workers and communities reliant on extractive industries. However, they tended to overlook the significant environmental impacts of these polluting enterprises and the strain on resources, which directly affects local communities near this infrastructure (Araujo et al., 2021). These concerns have been largely explored by research on environmental justice (Codato et al., 2024; Kopas et al., 2020; Sovacool and Scarpaci, 2016).

At the aggregate level, we also note a tendency in policy interventions to downplay or ignore the exacerbation of vulnerabilities resulting from delaying effective emissions reductions from continued fossil fuel use. In recent years, Brazil has experienced a surge in droughts impacting its hydropower energy infrastructure (Hunt. et al., 2018; Mendes and Sthel, 2018). Several factors may contribute to shifts in precipitation patterns and subsequent water and hydropower crises (Hunt. et al., 2018), including the impacts of El Niño events worsened by climate change, as well as intensive land transformation in the Cerrado (Paper II), where major river basins originate. Yet, to tackle the energy insecurity worsened by these droughts and escalating energy demand, an important aspect of the Brazilian government's long-term strategy has been to encourage the adoption of "abated non-renewable energy sources" (EPE, 2020, p.75).

Few studies have examined the impacts of climate change on thermal power plants with CCS and their anticipated increase in water requirements (Byers et al., 2016; Jin et al., 2022; Yang et al., 2020). In this case, for example, increased thermal energy emerges as a response to constraints on hydropower due to water scarcity. However, like hydropower, thermal energy is also expected to be affected by the impacts of climate change (Yalew et al., 2020). Beyond financial, material, labour, and regulatory demands, when operational, CCS is energy-intensive and requires water resources. This aspect might raise questions about their practical and technical feasibility in many instances, especially as resource constraints are exacerbated by a rapidly changing climate.

Like this, policy interventions often overlook the aggregate impacts of unabated climate change. This trend is similarly evident in climate change mitigation scenarios (Riahi et al., 2022). Namely, most of the authoritative global model-based scenarios that acted as a guiding compass to advance CCS policy intervention in this case (see quote at the beginning of this section) have a limited consideration of the impacts of climate change on mitigation potential, although knowledge on how climate change will alter the production and consumption of energy has increased over the years (Yalew et al., 2020). The neglect of unabated climate change impacts within policy interventions might stem from various political and economic motivations. However, it is counterproductive if models and scenarios intended to inform policy generate outcomes and recommendations that also neglect these issues. This perpetuates a feedback loop in which policymakers and researchers within the science-for-policy space consistently disregard the significant impacts of climate change. As demonstrated in this case, this oversight may lead to policy interventions that ultimately fail to align with their intended goals (i.e. energy security and just transitions).

Discussion

My aim in this thesis is to examine the politics of knowledge of CDR and its effects on climate governance, policy, and justice on the ground. In this section, I provide an overview of the main findings in relation to the politics of knowledge and justice. I also dive into the importance of reflexivity in doing science-for policy and contextualize this research within broader academic debates and diverse visions of the future.

Intersecting Justice and the Politics of Knowledge

In this thesis I set out to critically study the knowledge politics and effects of carbon dioxide removal as envisioned in modelled mitigation scenarios and how these relate to justice. Visions of the future that emerge from techno-economic framings of climate change are often presented as apolitical, as if they are detached from any historical context. Through the justice lens in Paper I, I show how such framings are in fact fundamentally political and situated within specific cultural hegemonic understandings of climate change: that of positivist scientific disciplines, natural scientists, and neoclassical economists. The global, value-neutral, and techno-economic framings that accompany the use of quantitative models further contribute to depoliticization. Yet, the assumptions that underpin ideas of value-neutrality break apart as soon as the practical implications become evident (Papers II and III). Disregarding the political nature of policy-relevant knowledge production can lead to fundamentally unjust outcomes and policy recommendations as they get translated into actionable imaginaries (Paper II) and concrete policy plans (Paper III). Ultimately, they risk serving dominant political agendas, leading to e.g. land concentration (Paper II) or the support of fossil fuel interests (Paper III).

Assertions of the normative dimensions of global knowledge production are not new in the literature. In recent years, a growing body of research has examined the potential and practical consequences of the decades-long effort of doing policy-relevant science (Beck & Forsyth, 2020; Böschen et al., 2010; Brown, 2015; Douglas, 2009; Jasanoff, 1990; Mahony & Hulme, 2016; Rayner, 2012). Decades of research have provided clear evidence on how research, and more specifically, policy-relevant work is fundamentally political (Jasanoff, 1990; Lövbrand et al., 2015; Miller, 2008; Turnhout, 2018). IAMs, for instance, may appear as being objective in their use of numbers and algorithms, but are fundamentally normative and value-laden in their framings, assumptions, methods, calculations and in the worldviews and realms of possibility they outline (Beck and Krueger, 2016; Beck and Oomen, 2021; Ellenbeck and Lilliestam, 2019; Lahsen and Turnhout, 2021). My primary contribution to this debate lies in the empirical focus of my work. In my analysis, I offer evidence supporting claims about the abstract techno-economic framework presumed in global models. These models are rooted in techno-optimist framings, which involve specific societal structures and power dynamics. This techno-optimism implies that it is politically implausible to imagine climate solutions that do not support and continue to benefit wealthier nations and global elites.

From a Global North – Global South perspective, my findings indicate that modelled scenarios treat the material aspirations of the Global South as outside of the realms of feasibility and policy relevance, while they place little or no constraints on the resource consumption in the Global North (and that of global elites in general). These assumptions of what is politically possible within models, are ultimately rooted in processes of capital and resource accumulation (Carton, 2019), and are deeply intertwined with colonial, gendered, and racialized practices of exploitation (Agarwal and Narain, 2019; Sultana, 2022).

Such assumptions are increasingly scrutinized by social scientists. One of the more recent studies to do so examined scenarios in AR6 and found that some of them anticipate extensive CDR efforts in regions of Asia and Africa, while simultaneously allowing continued oil and gas extraction and use in economically wealthier parts of the globe, like North America (Kanitkar et al., 2024). Through the way they project inequality into the future (see also Paper I), the models envisage a world in which, for example, by 2050, Sub-Saharan Africa has still not caught up with the average global GDP per capita in 2020 (Id.). That is, they project almost three decades during which economic growth is steered towards making rich nations richer, rather than lifting people out of poverty.

Other studies have revealed that inequitable energy access is assumed to persist in scenarios throughout the century (Hickel and Slamersak, 2022), with bioenergy-based negative emissions technologies contributing to address the high energy consumption of the Global North, while appropriating land in the Global South (see also (Bluwstein and Cavanagh, 2023). “On average, existing scenarios maintain the Global North’s energy privilege at a per capita level 2·3 times higher than in the Global South. Even the more equitable scenarios perpetuate large energy inequalities for the rest of the century” (Hickel and Slamersak, 2022, pg.e628). To some extent, this means that the Global North-South dynamics assumed in models (Paper I) replicate patterns of unequal economic (Emmanuel, 1972; Hickel et al., 2021b, 2022; Prebisch, 1959; Ricci, 2019) and ecological exchange (Dorninger et al., 2021; Foster and Holleman, 2014; Hornborg, 1998; Roberts and Parks, 2009). In simple terms, unequal economic and ecological exchange describes how patterns of resource use and extraction, as well as the resulting benefits and harms, are fundamentally uneven across countries and regions. This inequality in turn stems from asymmetrical power dynamics and historical processes of exploitation and value transfer.

Therefore, against this backdrop, one could argue that there seems to be a discrepancy between the outcomes projected in scenarios and the core equity principles inscribed in the UNFCCC and the Paris Agreement that they are aiming to inform and support. This also supports the imperative to for more justice-oriented research and praxis (Sultana, 2023). Ultimately, addressing this tension requires a concerted effort to bridge the gap between modelling practices and equity and justice principles, ensuring that mitigation scenarios, and ensuing policy recommendations, are not only cost-effective but also more equitable and just.

From global to local imaginaries

Global framings tend to perpetuate and reinforce existing erasures on the ground, including in the form of selective imaginaries that emerge in the process of translating global knowledge into national and local policy. These imaginaries often reflect historical practices of exclusion, segregation, and marginalization and are rooted in political economic relations that extend all the way to colonial times. Imaginaries serve as a bridge between past, present, and future, reshaping existing ideas to align them with evolving global priorities and framings. Frequently, these imaginaries, such as those promoting agro-industrial transformation in the Cerrado (Paper II) or advocating for just transitions to CCS development (Paper III), benefit vested interests and national and international elites. Meanwhile, the resulting harms disproportionately affect historically vulnerable and marginalized populations.

These concerns intersect with debates on environmental justice that highlight the often racialized and gendered effects of development projects, and the inequitable distribution of environmental benefits, harms, and decision-making opportunities. There are also parallels with critical literature on just transitions, which highlights the uneven impacts of new extractivist practices for the materials and minerals needed for the energy transition (Escosteguy et al., 2023; Hernandez and Newell, 2022; Jerez et al., 2021). Large extractive projects often come with attractive offers of progress, wealth and development for local populations, that in the end often fail to materialize (Codato et al., 2024; Davies, 2018; Forget and Bos, 2022; Kopas et al., 2020). Environmental justice scholars frequently call for the prioritization of the needs and voices of marginalized communities, offering valuable insights into the diverse concerns that may arise from various societal interventions envisioned in modelled scenarios.

Through the lens of indigenous climate justice, Whyte (2020) highlights that colonial, capitalist, and industrial systems have historically – and continuously –

inflicted violence and harm upon indigenous peoples, subjecting them to threats and injustices similar to those posed by climate change today. These include biodiversity loss, ecosystem collapse, mass migration, cultural disintegration, and economic crises. From this vantage point, it becomes obvious how the indigenous and local populations of the Cerrado, have experienced the agro-industrial transformation of their landscape as a manifestation of these multiple layers of systemic violence. Yet, to this day, local, vulnerable, indigenous, and racialized populations continue to be erased in new sociotechnical imaginaries and nation-building efforts (see Paper II). They are excluded from opportunities for framing, engaging with, and developing policies and projects that affect them directly. More broadly, they still struggle with epistemological credibility, that is, to be recognized as possessors and creators of knowledge, a concern raised in academic debates under the flag of both epistemic and cognitive justice.

The prevalence of dominant national imaginaries and visions of the future does not negate the existence of alternative, counter-hegemonic imaginaries. These persist in the background as spaces of resistance and as places for envisioning and inhabiting alternative futures. They serve as spaces of prefiguration, where the desired values, principles and visions desired for a future society are embodied and enacted in the present (Jeffrey and Dyson, 2021; Swain, 2019; Yates, 2021). They represent radical collective efforts where local, social, and political movements explore alternatives and reshape practices, discourses, and power structures, as if the future was already here (Davoudi, 2023; Ullström, 2024; Yates, 2015). In Brazil, for example, the Landless Movement (Movimento dos Trabalhadores Rurais Sem Terra) has a long history of prefiguring (McCowan, 2010; Törnberg, 2021) and imagining counter-hegemonic forms of organizing, living in and with the land, and producing food (Karriem, 2009; Loureiro and Zarref, 2021). At a more global scale, La Via Campesina, one of the world's largest social movements, works towards a fundamentally restructuring the food production system, promoting food sovereignty and agroecology. These collective efforts can serve as radical examples to broaden the spectrum of plausible futures examined in modelling and other future-oriented research efforts.

Other paths to justice: Imagining more and alternative futures

IAMs, have been instrumental in mobilizing policy efforts for climate change at the local and global level, and have gained a strategic role in WGIII of the IPCC. However, the inherent uncertainties that pervade attempts to model global mitigation scenarios, coupled with the multitude of variables, policies, climatic, societal, and economic parameters, and assumptions makes them inadequate tools for guiding global decades-long climate action. Still, they have a central role in global assessments (e.g. IPCC, IEA), and are unlikely to leave the spotlight anytime soon. Therefore, we need to work both with and without them to imagine alternative futures.

Ideally, a key concern in mitigation modelling efforts should be to focus on the implementation of stringent – yet equitable – mitigation scenarios in the short to medium term (Rosen and Guenther, 2015), rather than decades-long global mitigation trajectories. However, if long-term global modelling efforts are to continue, it is imperative to explore new, alternative futures while operating within their methodological constraints.

First, researchers in this field (and in policy-relevant efforts overall) should engage in open and critical reflection to understand and acknowledge their biases, values, and normative perspectives. Engaging with critical social sciences and empirically grounded research can serve as an entry point to reveal and better understand the biases, normativities and values that we carry over in our work as researchers, but that might not be easily visible to ourselves. Further, insights from critical scholarship can provide an entry point for reflexivity to the extent that it allows for a deeper understanding of complex socioenvironmental issues and the effects of societal interventions and development projects. This was a key motivation for the interdisciplinary engagement in my three papers.

A second step should be to diversity the parameters, assumptions, and inputs of models, for instance by engaging with other disciplines or branches of economic thought. But it could also include increased responsiveness to other disciplines, voices, and societal demands, for instance climate justice or calls for equity and justice from the Global South.

Third, and most importantly, we need to foreground alternative visions of the future beyond algorithmic models. IAMs should not be the only tools used and assessed by the IPCC for exploring and imagining climate futures (Gambhir et al., 2022). Alternative tools exist that could help open up spaces to imagine alternative futures. Some of these tools are relevant for scenario modelling efforts with IAMs, but also for other policy-relevant forms of research. Below, I outline some of these alternatives.

Diversifying economics

One of the strengths of IAMs is that they can dynamically simulate numerous societal demands and interactions. Yet, as noted in Paper I, the narrow economic assumptions and parameters in models seem to mainly yield policy recommendations aligned with fundamentally unjust neoliberal climate policies. Neoclassical economics has provided the framework for neoliberal politics, shaping its policy prescriptions and guiding principles. This is at the core of the numerous intersecting crises that we live in now, and at the core of the unjust modelled outcomes, policy recommendations and future oriented interventions (Papers II and III). One pragmatic approach to addressing this limitation could involve integrating insights and assumptions from alternative branches of economic thought, i.e. heterodox economics (Proctor, 2023). This could provide a more comprehensive exploration of broader social, ethical, ecological, and political considerations.

Approaches inspired by ecological economics have seen a resurgence over the past decade and reckon more attention in this space (Raworth, 2017; Schlesier et al., 2024) similar to approaches from degrowth that have already began to be incorporated in global energy and mitigation scenarios (Keyßer and Lenzen, 2021; Kikstra et al., 2024). As opposed to neoclassical economics, many of these schools of thought have been influenced by, for example, the unequal exchange traditions (Foster and Holleman, 2014; Hornborg, 2014, 1998). By examining patterns of unequal exchange in natural resources, such as land, water, minerals, and biodiversity, they could shed light on the power dynamics, injustices, and consequences that arise from the unequal distribution and exploitation of resources within and among regions. These issues remain largely overlooked in modelling efforts (Hickel et al., 2021a; Keyßer and Lenzen, 2021).

Another important endeavour for the economics of climate change research, and science-for-policy research at large, should be to revisit the contributions from Global South scholars that have been marginalized in the field of International Political economy – including by heterodox economics – (Antunes de Oliveira and Kvangraven, 2023). Dependency theory, for instance offers insightful and policy-relevant perspectives from a Global South, non-Eurocentric and anti-colonial standpoint (Amin, 1988; Bambirra, 1978; Chang, 2011; Frank, 1998; Furtado, 1978; Tavares et al., 2000), but are often disregarded in mainstream international political economy debates (and curriculums). Welfare economics grounded on needs-based and capabilities principles (Sen, 1970), or development economics (Margulis, 2019; Prebisch, 1959) can also bring other insights. These various perspectives could provide valuable talking points for policy makers and other societal stakeholders, showcasing a variety of ways to reduce demand (Mundaca et al., 2019), while still ensuring a decent quality of life (Creutzig et al., 2018; Millward-Hopkins et al., 2020; O'Neill et al., 2018).

When it comes to societal changes, other intergovernmental reports (UNEP, 2023), and other sections of the IPCC assessments clearly emphasize the necessity of curbing the consumption patterns (and emissions) of global elites if we are to achieve the goals outlined in the Paris Agreement in a more equitable way. To address this, some have argued for the inclusion of a more systematic exploration of extremes in scenario research (McCollum et al., 2020). These extreme and disruptive events, whether rare or unforeseen, can have a significant impact, often serving as catalysts for societal change and redirecting society towards new paths. They can manifest in various ways, including weather events, financial crises like the 2008 recession, prolonged wars, shifts in political ideologies, technological innovations such as mass automation and AI, or changes in consumer behaviour and preferences. For instance, the 'low energy demand scenario' proposed by Grubler et al., (2018) outlines a global pathway aimed at limiting temperature rise to 1.5°C, surpassing even the most ambitious sustainable projections such as SSP1 Sustainability: Taking the Green Road (Grubler et al., 2018; McCollum et al., 2020).

In sum, numerous options exist to broaden the parameters that are considered and to expand the boundaries of models. These have for instance translated into efforts to explicitly include equity considerations in scenarios (Emmerling and Tavoni, 2021; Klinsky and Winkler, 2018), or to generate more scenarios that take into account the risk of mitigation deterrence from CDR (Grant et al., 2021). There have also been suggestions on how to better consider the legal boundaries of different societal interventions by incorporating legal and governance elements to scenario modelling efforts (Triyanti et al., 2023). Finally, scholars have also put forth ideas to engage more with climate fiction in models (Van Beek and Versteeg, 2023), or to collaborate more with the arts and humanities (Braunreiter et al., 2021).

Non-modelling futures

Beyond IAMs, there is a broad range of methods for future analysis that has been largely overlooked in climate change mitigation research (Gambhir et al., 2019). Futures thinking plays a central role in sustainability studies, and the field has witnessed a surge in participatory scenario development and future visioning approaches in recent years (Johansson, 2021; Mangnus et al., 2021; Muiderman et al., 2020). While participatory approaches have often faced critique for lacking the potential to stimulate empowerment and social change (Johansson, 2021), some allow for a more balanced conversation between traditional or activist knowledge and more formal, academic knowledge. Examples include the use of participatory approaches to envision agroecological futures and the political action needed to support them (Johansson et al., 2023), and the use of "techniques of futuring" to explore energy and sustainability transitions (Oomen et al., 2021).

Incorporating other voices: an effort of knowledge translation

For decades, developing countries, and other underrepresented voices from the Global South, social movements, and indigenous communities have voiced concerns about the fundamental inequities inherent in the causes, consequences, and responses to climate change (ICJN, 2002; IEN, 2012; La Via Campesina, 2018), as well as the science that produces them (Kanitkar et al., 2024; Kartha et al., 2018; Parikh, 1992). Researchers in the science-for-policy space could engage in more transdisciplinary efforts to translate some of these concerns into the language of models, but also in broader academic research. Transdisciplinary engagement is key to shed a light on the multiple considerations that are lacking in science-for-policy efforts, and to engage with the kinds of expertise that have historically been left behind.

People with expertise coming from non-academic spaces, often lack the technical language or access to resources to engage with the intricate discourses of science—particularly in the realm of science for policy. In academic circles, some of the critical social sciences, such as political ecology and environmental justice, have a rich tradition of examining and documenting insights and struggles from the Global South. Collaborating in interdisciplinary teams with researchers from these fields could also offer a pathway for integrating some of their insights into the science-for-policy endeavour. I expand on this in the next subsection of this chapter, but first, a word of caution is necessary.

While recommendations for knowledge translation, and interdisciplinarity, offer one avenue for raising the visibility of previously marginalized societal concerns, there are also risks involved. As Markusson et al. (2020) argue, techno-economic framings (such as those of IAMs) are too constrained to be able to analyse complex social dimensions, and therefore risk limiting what is considered relevant in social science (Markusson et al., 2020). Moreover, increased interdisciplinarity by itself does not resolve the fundamental issues of epistemic and cognitive (in)justice pervasive in knowledge production and decision-making processes—namely, who gets to be considered a knower and which forms of knowledge are deemed valid. It only lends these claims a stamp of credibility and authority by translating them into the complicated and – often – exclusionary language of scholarly research. In other words, they still rely on Eurocentric frameworks and voices to bring concerns forward. This dynamic perpetuates the notion that legitimate theoretical work occurs only in the North, relegating the Global South primarily to a site of data collection (Connell et al., 2018; Hountondji, 1997).

The academic system – and not just models – encapsulates and replicates the numerous layers of power imbalances and structural injustices between the Global North and Global South, which ultimately determine whose worldviews, ideas and methods are heard, represented, and validated. This highlights the critical necessity of promoting epistemic justice within academia. Epistemic justice (Fricker, 2003; Medina, 2017) strives to bring these struggles forward; it is an endeavour that goes beyond just models, and is relevant to all other ways of doing science and policy as well. It is an effort that would require a commitment to challenging existing power dynamics, centring voices and perspectives that have been historically sidelined (see also the Diversifying Economics section) and fostering inclusive and equitable practices in knowledge production and dissemination.

Plural futures from the margins

Theorization emerging from non-hegemonic traditions can provide a deeper analysis of the articulations of knowledge and power that elicited the processes of marginalisation in the first place (Harding, 2001, 1986). Both feminist and decolonial scholarship have elucidated the social and epistemic mechanisms of exclusion in the production – and validation – of scientific knowledge, embodied in structural barriers such as gendered practices (Haraway, 1988; Harding, 1986), or historical marginalization of non-western science and knowledge practices (Mignolo and Escobar, 2013; Santos et al., 2008). These approaches offer an opportunity to critically analyse the role of global models and algorithms in addressing societal issues, demystify their functions, deconstruct assumptions, and examine impacts from perspectives complementary to those used in this thesis.

Decolonial scholars, for instance, have linked the colonial legacy in academia to the economic structures since the 16th century. They have analysed how knowledge structures are supported and co-produced by capitalist exploitation (Grosfoguel, 2022, 2007). Decoloniality is not about how hegemonic (western) knowledge looks at the rest of the world, but how the rest of the world reconstitutes its ways of living and thinking in relation to the West (or the Global North). Through a critique of globalism, decolonial theory challenges "the global design of a local history", which is the history of the North Atlantic as universal or global (Mignolo, 2021; Mignolo and Escobar, 2013).

Against this backdrop, decolonial scholarship offers an entry point to engage with other knowledge systems and traditions for more holistic visions of the world, enabling greater epistemological diversity in the quest for more diverse and equitable climate and social futures – or as Escobar put it, for more "Pluriversal" futures (Escobar, 2017). Pluriversality entails a political vision of the world in which multiple ontologies, practices and ways of living can co-exist (Kothari et al., 2019; Mignolo, 2021). Pluriversal futures entail a fundamental shift in values, institutions, and ways of relating to one another and to the world around us and is a way to strive for cognitive justice. This engagement also helps to move past the limitations of academic knowledge and social theory to deal with many of the concerns (Escobar, 2017). It is also in these spaces, through the interaction with other knowledges, where the real space of possibility lies (Shiva, 1993).

Cognitive justice (Santos, 2008) strives for the recognition and validation of diverse knowledge systems and ways of knowing that have historically been marginalized or excluded from mainstream discourse. Social justice cannot be achieved without cognitive justice, and cognitive justice is essential to fundamentally challenge and transform broader societal injustices at their core (Santos, 2008). Indigenous worldviews and practices have been marginalized from the mainstream discourse for centuries and entail, among other things, a fundamental recognition of the interdependence between humans and nature. These practices are not just discursive or metaphorical but come accompanied with efforts of resistance and struggle to resist colonial and capitalist forms of oppression and reclaim autonomy and sovereignty over their cultures (IEN, 2012; The Red Nation, 2021) and their lands (Tuck and Yang, 2012). Similar to indigenous peoples, many local communities and social movements in the Global South embody ontologies, practices, and visions of the future that fundamentally reconsider life in the present while reimagining and working toward a better future. These visions manifest in notions such as Buen Vivir, the rights of nature (CMPCC, 2010), post-development, and transitions to post-extractivism (Escobar et al., 2022; Kothari et al., 2019).

Alternative Carbon Removal Futures?

A central concern of this thesis revolves around the role of CDR in visions of the future. I have illustrated the politics of knowledge that brought them into being and the fundamentally unjust effects they could have. However, a critical open question remains against this backdrop: Can CDR ever be just?

At a global scale, and in scenarios, CDR is framed as a necessary globally coordinated effort aimed to deal with the ultimate global threat posed by climate change. However, these arguments often fail to recognize that in the ways and scale at which CDR is envisioned, its implementation would place a disproportionate burden precisely on the vulnerable populations that are already threatened by climate change, and by the way we've organized society overall. In other words, these claims often forget the politics of resource use and extraction inherent to CDR. In this way, vulnerable populations, mainly in the Global South, are once again left to bear the burden of the consequences of and solutions to climate change. I make this visible in the multiple erasures and processes of dispossession for carbon sequestration, biofuels (Paper II) or in the case of CCS – and BECCS-, the intensive resource requirement (e.g., water), pollution and large energy penalty required for its operation (Paper III).

2023 was the first year where global average temperatures exceeded 1.5C for the entire year (C3S, 2023). We already live with an excess of GHGs in the atmosphere, and some sources of emissions will remain, even after all emission reduction options are exhausted. CDR could help to counterbalance those residual and hard-to abate emissions (Buck et al., 2023; Rogelj et al., 2021).. Some suggestions on how to implement and govern CDR efforts have been sketched in the literature. Radical emissions reductions on all sectors, and a rapid and equitable fossil-fuel phaseout are the first critical and obvious steps, because without this, CDR would barely make a dent in emissions reductions, as current numbers show (Powis et al., 2023). Questions of scale are therefore important, and any research and deployment of CDR should be done only to complement emissions reductions efforts under the precautionary assumption that CDR will not work at scale (Anderson and Peters, 2016). CDR efforts at smaller scale, and from a diversity of methods (Nemet et al., 2018) could have less socio-ecological and environmental impacts and not compete with other priorities.

Principles have been proposed in the literature for CDR governance in the context of just climate policy (Morrow et al., 2020), and to avoid delaying emissions reductions (Höglund et al., 2023; Rogelj et al., 2021). Some important recommendations include: separating reduction and removal targets (Grant et al., 2021; McLaren et al., 2019), dealing with residual emissions (Buck et al., 2023), or demanding like-for like compensation (i.e. permanent storage for fossil carbon, biological storage for biogenic carbon) (Höglund et al., 2023; Smith et al., 2023), as well as thoroughly considering the societal impacts and co-benefits of the different methods (Anderson et al., 2023; Fuss et al., 2018). Therefore, CDR could play a role in more plural and just futures, but under a limited scale and with clear governance arrangements.

Concluding Remarks

This thesis is an attempt to re-politicize a conversation that has been technicalized, and to some extent to "resituate" knowledge framed as global, technical and value neutral. In this attempt, I emphasize the significance of engaging with justice concerns in a space that has largely avoided dealing with justice. I argue that, through a lack of explicit engagement with justice concerns, Integrated Assessment Models for climate mitigations and their results can continue to perpetuate or even amplify old injustices and hidden biases (Paper I), normalizing and leading to fundamentally unfair outcomes, historical erasures (Paper II) and unjust policy recommendations (Paper III).

Science for policy cannot be a-political, nor value neutral. All forms of action or inaction have normative implications. Value neutrality under the idea of consensus is problematic and contributes to vested interests and closes the space of possibilities. Research intended to provide evidence and support decision-making must go beyond notions of cost-efficiency and techno-economic feasibility, and equal weight needs to be placed on other ways of supporting decision-making (i.e. Justice).

I hope this research is read as an invitation for scholars engaged in science-for-policy research to take a step back and critically reflect on the normativities and biases inherent in their methods and approaches, and the types of narratives and political agendas they might inadvertently support, reproduce, and reinforce through their work. I also hope it serves as a catalyst and a door opener to exploring alternative futures for a planet in crisis, within but mainly beyond the realm of computer models. As researchers, while trying to remain policy-relevant, we limit our explorations and visions of alternatives, either because we see them as less possible, due to the constant reminder of constraints and trade-offs that exist, or because these alternatives are simply impossible for us to imagine.

Numerous structural factors contribute to decision-making, and changing some parameters in models and putting forward other ways to envision future scenarios will not change the world, it will not end capitalist systems of oppression, inequality, and maldistribution, it will not stop climate change. However, at the very least, it will not continue to legitimize a system that benefits a few as if "there is no alternative."

There are alternatives, and now, more than ever, we need more of those alternatives to envision other, better futures for everyone. Diversifying knowledge is central to this effort, and it remains a pending task in the science-for-policy research space. It shouldn't be radical to explore policy options within what is fair and possible within the biophysical limits of the planet, rather than what is deemed technically feasible or economically desirable for a few.

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