Implications of Climate Change and Ecosystem Services Degradation for Macroeconomic and Financial Stability

Maximilian Auffhammer
Elías Albagli
Sofía Bauducco
Gonzalo García-Trujillo
editors

Banco Central de Chile / Central Bank of Chile

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The accelerating degradation of climate and natural ecosystems presents profound challenges for ensuring macroeconomic and financial stability. This volume explores the complex and systemic risks posed by climate change and lost ecosystem services through the lens of cutting-edge economic research. Drawing on contributions from leading scholars, the collected papers underscore the importance of adopting an integrated, multidisciplinary approach to address the risks posed by climate change and the degradation of ecosystem services. They collectively highlight that fostering technological innovation, incorporating the value of natural capital into macroeconomic decision-making, embedding ecological and climate-related risks into financial oversight, and advancing coordinated policy frameworks are all critical for building resilient and sustainable economic systems. As environmental pressures continue to build up, the implications of climate change and ecosystem services degradation intensify. The insights and strategies presented here offer a coherent roadmap for researchers, policymakers, and financial institutions seeking to preserve macroeconomic and financial stability in the face of escalating nature-related crises.

Cajón del Maipo (Valle del Yeso)
Luis Strozzi
Oil on canvas, 138 x 194 cm
Collection of the Central Bank of Chile

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Implications of Climate Change and Ecosystem Services Degradation for Macroeconomic and Financial Stability: An Overview

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This volume collects some of the papers presented at the XXVI Annual Conference of the Central Bank of Chile, which took place in November 2023 in Santiago, Chile.[1] The theme of the conference was **Implications of Climate Change and Ecosystem Services Degradation for Macroeconomic and Financial Stability**. The main objective of the conference was to bring together a select group of economists in the fields of environmental economics and macroeconomics dedicated to exploring the impacts of natural resource degradation on macroeconomic and financial stability.

In recent decades, we have observed an accelerating degradation of natural systems, with tangible and escalating consequences. Numerous countries are now experiencing more frequent and intense extreme heat events, elevated maximum temperatures, declining river flows, and an increase in large-scale fires, droughts, and other forms of climate-related disruption. The Intergovernmental Panel on Climate Change (IPCC) underscored these developments in its 2022 Sixth Assessment Report, which delivered a stark message: there remains a growing gap between the emissions trajectory required

1. The full program is available on the Central Bank's webpage.

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to meet the objectives of the Paris Agreement, specifically limiting global warming to 1.5°C or, at most, 2°C by the end of the century, and the emissions pathways implied by current Nationally Determined Contributions.[2] As the report states, "current climate pledges to 2030 would make it 'impossible' to limit warming to 1.5°C with 'no or limited overshoot'—and 'strongly increase the challenge' for 2°C." Parallel to this, the 2019 Global Assessment Report on Biodiversity and Ecosystem Services, released by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), presents extensive empirical evidence of a rapid and ongoing global decline in biodiversity. The report estimates that 75% of terrestrial environments and 66% of marine areas have already undergone substantial human-induced change. Together, these findings indicate that while ecological systems are issuing increasingly urgent warnings about the risks of a delayed green transition, global responses continue to follow a path characterized by insufficient urgency and late-stage intervention.

The IPCC's emphasis on achieving "no or limited overshoot" highlights the critical importance of the emissions trajectory en route to net zero by mid-century. Even a temporary overshoot beyond the 2°C threshold entails substantial risks and costs. Such a deviation would not only increase the economic burden of transition—potentially necessitating large-scale deployment of carbon dioxide removal technologies—but also heighten the likelihood of breaching climate tipping points. This, in turn, would elevate the probability of widespread and irreversible impacts, including damage to built infrastructure, displacement in low-lying coastal regions, and degradation of ecologically sensitive zones such as polar, alpine, and coastal ecosystems.[3] These consequences carry systemic implications, as the resilience of human societies is fundamentally tied to the stability and continued functioning of the diverse ecosystems upon which we rely.[4]

Beyond the direct climatic consequences, a delayed transition poses substantial systemic risks to human welfare and geopolitical stability. The disruption to the well-being of billions of people over the coming decades has the potential to catalyze complex secondary effects, including large-scale migration flows, intensified domestic political polarization, and heightened international tensions. The cumulative

2. IPCC (2023).
3. See OECD (2022).
4. See, for example, Dasgupta (2021).

societal and economic costs associated with these dynamics may far exceed the investments required to implement a timely and effective climate and environmental transition. Accordingly, it is imperative to expedite mitigation strategies while simultaneously advancing adaptation measures aimed at enhancing economic resilience throughout the transition to net-zero emissions.

It is equally essential to recognize that the policies and investments required to facilitate the net-zero transition will carry macroeconomic implications. On one side, the scale of additional capital expenditure needed may place upward pressure on the cost of capital, and certain tax instruments designed to incentivize the shift toward cleaner energy sources may introduce market distortions that could, in turn, influence growth trajectories. However, it is equally important to underscore that, as with any major structural transformation driven by large-scale investment, the transition holds the potential to generate net positive economic outcomes over the medium term, beyond its environmental gains. These benefits include downward pressure on long-term energy prices and the creation of new employment opportunities and business ventures in sectors positioned to expand within a more sustainable global economic framework.

To shed light on these challenges, this volume presents seven papers, as well as two keynote addresses, delivered by Philippe Aghion and Maximilian Auffhammer, that provide critical insights into four topics: macroeconomic impacts of climate change, macroeconomic impacts of ecosystem services degradation, climate change and biodiversity loss as a financial risk, and climate change and ecosystem services degradation from a multidisciplinary perspective.

The first three papers examine the macroeconomic consequences of climate change, underscoring that climate risks are not tangential but fundamental to contemporary macroeconomic analysis and policy design. These papers argue for the urgent integration of environmental considerations into economic decision-making frameworks.

The opening paper, authored by Cédric Crofils, Nicolás Durán, Javier Ledezma, Víctor Riquelme, and Juan M. Wlasiuk, entitled **Central Banks and Sustainability: A Comprehensive Review of Green Mandates, Speeches, and Actions**, presents a detailed review of how 125 central banks are incorporating environmental objectives into their mandates, communications, and operational activities. Prompted by the growing consensus that climate risk poses a threat to financial stability, the authors systematically assess speeches, policy statements, and institutional initiatives across

major jurisdictions. Their analysis categorizes instruments such as climate scenario modeling, stress testing, and mandatory disclosures, documenting their adoption over time.

The findings point to a gradual but clear shift: central banks are increasingly embedding sustainability within their mandates, both formally and informally, as well as within their public communications. There is also a marked uptick in central bank research output on climate-related topics, which reflects a growing institutional commitment to understanding environmental risks and exploring their macrofinancial implications. The study also identifies significant variation across countries: central banks in wealthier and larger economies show greater levels of engagement, while those in countries with high inflation or heavy dependence on natural resources tend to be less active. Notably, stronger democratic institutions and higher exposure to climate risks correlate positively with greater central bank involvement in environmental issues.

The Short-Run Macroeconomics of the Energy Transition: A Review and Directions for Research, by Adrien Bilal and James H. Stock, surveys the growing empirical literature on the near-term macroeconomic implications of energy transition policies, with a particular emphasis on policy uncertainty, geopolitical transition risks, and the inflationary pressures associated with decarbonization. Recognizing the transition to a low-carbon energy system as one of the most consequential structural shifts currently confronting the global economy, with far-reaching effects on macroeconomic stability, international relations, and policymaking, the authors aim to synthesize current empirical insights and chart a course for future research.

Their review yields two principal conclusions. First, large-scale climate policies, those that encompass a substantial share of emissions and economic activity, can exert contractionary effects on short-run real economic output. However, the magnitude and persistence of these effects hinge critically on policy design. Climate policies that deliver predictable and gradual carbon pricing, such as a well-calibrated carbon tax, tend to generate fewer adverse economic effects. In contrast, those introducing high levels of volatility and uncertainty in carbon pricing, such as certain cap-and-trade mechanisms, are more likely to disrupt macroeconomic conditions. The authors thus advocate for policy architectures that minimize volatility in both explicit and implicit carbon prices. Second, recent inflationary episodes (notably from 2021 to 2024) appear to have been partly driven by energy market

disruptions, a trend likely to continue. Even under ambitious net-zero scenarios, fossil fuel demand in advanced economies is expected to remain significant due to inelastic consumption patterns and slow supply adjustments. Given the structure of global energy markets, this persistence implies ongoing exposure to geopolitical risks and supply-side shocks. Bilal and Stock argue that, while central banks have developed tools to manage traditional energy supply disruptions, there is an urgent need to deepen our understanding of how these shocks will evolve in the context of decarbonization.

Next is the keynote lecture by Philippe Aghion, **Innovation, Growth, and Environmental Challenges: Schumpeterian Insights into Climate Change and Green Technologies**, which explores how the macroeconomic considerations of the energy transition, outlined in the preceding paper, intersect with the role of innovation in achieving sustainable growth. Drawing on a Schumpeterian framework, Aghion emphasizes that the mechanism of creative destruction, whereby new technologies and firms displace outdated incumbents, can simultaneously drive long-run economic growth and support decarbonization. He argues that sustained growth is rooted in the accumulation of innovations, spurred by the prospect of entrepreneurial rents. However, the innovation process is both dynamic and path-dependent, thus requiring a carefully constructed policy mix. While carbon pricing is necessary to internalize the environmental externalities of emissions, it is insufficient on its own. Complementary industrial policies, such as targeted R&D subsidies and direct support for clean technologies, are also required to overcome market failures specific to green innovation.

Aghion directly engages with the "degrowth" position, challenging the notion that halting or reversing economic growth is either necessary or effective in addressing environmental degradation. Instead, he advocates for a strategy of directed technological change, deliberately channeling innovation toward low-carbon solutions, as a viable and constructive response. His argument is grounded in the idea that, under the right institutional arrangements and incentive structures, economic growth and environmental sustainability are not in conflict. Rather, they can be aligned, with green innovation serving as the mechanism that reconciles ecological imperatives with continued prosperity.

The following two papers shift the focus toward the macroeconomic implications of ecosystem services degradation.

Integrating Ecosystem Modeling into Economic Models: Applications to Efficiency Analysis, Gross Ecosystem Product, and Policy Analysis, by Stephen Polasky, underscores the necessity of embedding ecological modeling within economic frameworks to more effectively manage the sustainable use of natural capital. Ecosystems deliver foundational services, such as pollination, water purification, and climate regulation, which are critical to both human welfare and economic systems. Yet, due to their public good nature and the persistence of market failures, these services are frequently undervalued, overlooked, and inadequately protected. This raises the imperative for more integrated modeling approaches that can better characterize ecological vulnerabilities and guide the design of more sustainable policy responses.

Polasky introduces a biophysical-economic modeling framework that couples ecological process models with economic valuation tools to quantify how anthropogenic pressures, such as habitat loss, pollution, and overexploitation, erode ecosystem services and, by extension, affect macroeconomic outcomes. The framework begins by assessing the biophysical impacts of human activities, including land conversion, emissions, and resource extraction, and translates these into quantifiable changes in ecosystem services. These changes are then linked to economic indicators of well-being and productivity. The model also incorporates policy mechanisms, such as payments for ecosystem services, targeted conservation incentives, and environmental taxation, which influence land use and resource management decisions. This integrated approach highlights the risks of excluding ecological dynamics from economic analysis, leading to underestimation of system-wide vulnerabilities. It also demonstrates that well-designed conservation and land-use policies can yield substantial long-term economic benefits while strengthening resilience to environmental shocks.

In a similar vein, and motivated by the recognition that conventional macroeconomic models tend to overlook the finite and fragile character of natural capital by assuming unlimited resource availability and infinite waste absorption capacity, the paper titled **Introducing Natural Capital in Macroeconomic Modeling**, by Nicoletta Batini and Luigi Durand, seeks to address this conceptual gap. The authors extend a standard neoclassical growth framework, akin to the Solow model, to explicitly incorporate natural resources and ecosystem services. The model distinguishes between renewable and non-renewable resources, capturing their regeneration and depletion

dynamics, intrinsic stock growth rates, and the ecological thresholds that constrain sustainable use. It also differentiates between notions of sustainability, comparing strong sustainability—where natural capital must be preserved or enhanced over time—with weak sustainability, which permits substitution between natural and human-made capital. Within this extended framework, Batini and Durand examine how policy instruments, including environmental taxation, property rights, and technological innovation, affect the evolution of natural capital and, by extension, macroeconomic performance.

The model demonstrates that excluding natural capital from macroeconomic analysis significantly understates the risks of economic and financial instability. Long-term economic growth depends on the preservation of biodiversity and ecosystem services, and their degradation can trigger adverse macroeconomic shocks and diminish overall welfare. The framework also shows that policies promoting sustainable resource use, such as conservation strategies, innovation in resource-efficient technologies, and secure property rights, contribute to more stable and resilient economic trajectories. Crucially, the analysis reinforces the importance of incorporating ecological constraints directly into macroeconomic modeling to avoid the long-run costs associated with biodiversity loss, resource depletion, and ecosystem collapse.

While renewable energy sources such as solar, wind, and hydropower are essential for reducing carbon emissions and addressing climate change, their expansion can inadvertently pose risks to biodiversity and ecosystems through habitat modification, pollution, and resource overuse. Motivated by this inherent tension, the paper **Biodiversity vs. Climate Risk Exposures of Renewable Energy Firms**, by Johannes Stroebel and Xuran Zeng, investigates the extent to which renewable energy companies are exposed to biodiversity-related transition risks and how these exposures influence financial outcomes and investor behavior. To examine this question, the authors analyze corporate risk disclosures, including 10-K filings, and compare the risk profiles of renewable and nonrenewable energy firms. They focus on key transmission channels, including land-use change, habitat disruption, environmental pollution, and resource extraction, all of which may harm biodiversity and generate regulatory or reputational repercussions. In addition, they study how financial markets respond to news about climate and biodiversity risk realizations, linking these responses to stock price movements.

The findings indicate that renewable energy firms report greater exposure to biodiversity risks than their nonrenewable counterparts, largely due to the ecological disruptions associated with project development. Although these firms benefit from lower exposure to climate transition risks, owing to their alignment with global decarbonization goals, their financial performance remains sensitive to biodiversity-related concerns. Empirical analysis of stock returns shows that renewable energy portfolios respond positively to news signaling progress on climate policy, reflecting investor optimism about climate mitigation. In contrast, these same portfolios underperform following news events highlighting biodiversity risks, suggesting that markets perceive such risks as material and adverse. The authors conclude that the large-scale deployment of renewable energy infrastructure, if poorly managed, may conflict with biodiversity preservation objectives. As such, explicitly incorporating biodiversity risk into investment and policy decisions is essential for achieving a sustainable and resilient energy transition.

The keynote lecture by Maximilian Auffhammer, titled **The Social Cost of Carbon—What's New and Next**, offers a detailed overview of recent developments in the estimation of the Social Cost of Carbon (SCC), with particular attention to how advances in empirical economics, climate science, and discounting theory have reshaped the modeling tools employed in U.S. federal climate policy. Auffhammer traces the evolution of the SCC through improvements in integrated assessment models, including DICE, FUND, and PAGE, and explains how recent methodological innovations—such as probabilistic modeling of climate sensitivity, empirically grounded, sector-specific damage functions, and the explicit treatment of catastrophic tail risks—have led to more nuanced and robust estimates.

He notes that the current central estimate of the SCC, approximately USD190 per metric ton, reflects these technical advances, although substantial uncertainties remain. These include the specification of sectoral damages, geographic heterogeneity in climate impacts, and the challenge of modeling low-probability, high-impact outcomes. Auffhammer emphasizes the importance of further refinement through improved regional granularity, dynamic risk modeling, and more precise estimation of economic damages. He also addresses the normative debates surrounding discount rates and intergenerational equity, both of which significantly influence the SCC's magnitude. Auffhammer advocates for continued research to enhance the credibility and policy relevance of SCC estimates, which

remain central to the design of effective mitigation strategies. He concludes that, while the SCC is a critical metric for aligning economic decision-making with climate objectives, its reliability and thoughtful application are essential to avoid the most severe consequences of unmitigated emissions.

The volume concludes with two papers examining the impacts of climate change and ecosystem service degradation from a multidisciplinary perspective.

The first one, **The Possibility and Plausibility of Large Macroeconomic Impacts from Climate Change**, by Marshall Burke, Mustafa Zahid, and Solomon Hsiang, explores whether the risk of catastrophic macroeconomic impacts has been systematically underestimated. Drawing on empirical evidence of severe climate consequences and ecological feedback mechanisms, the authors use global historical panel data to estimate the relationship between temperature variability and national economic growth. They uncover a nonlinear relationship in which countries with hotter climates suffer disproportionately from incremental warming. By combining these empirical estimates with climate model projections under various emissions scenarios, they simulate potential effects on both global and country-level economic output over the course of the twenty-first century.

Their analysis suggests that, by 2100, global economic output could decline by approximately 10 to 30 percent relative to a no-warming baseline. Under conservative assumptions that exclude lagged temperature effects, estimated impacts are around 10 percent. However, when accounting for lagged effects—which better reflect empirical patterns—losses could reach as high as 30 percent. These projections are considered plausible, as they fall within the range of historical growth fluctuations and are consistent with recent Bayesian forecasts of economic trajectories. While impacts vary across countries, some of the most affected regions, including parts of Africa and the Middle East, may face economic disruptions beyond their historical experience, raising significant concerns for growth, stability, and resilience in vulnerable economies.

The second and final one, **Through Drought and Flood: Past, Present, and Future of Climate Migration**, by Elías Albagli, Pablo García, Gonzalo García-Trujillo, and María Antonia Yung, investigates the historical role of climate variability in shaping migration patterns and projects potential future flows under a range of climate scenarios. The first part of the paper adopts a narrative approach centered on four

historical episodes: the collapse at the end of the Bronze Age (circa 1200 BCE), the decline of the Eastern Mediterranean civilizations (circa 1000 ACE), the Bhola cyclone and the Indo-Pakistani War leading to the formation of Bangladesh in 1971, and the Rwandan genocide and subsequent conflict in the Congo Basin between 1994 and 2001. Across these cases, the authors document that severe climate disruptions have historically triggered substantial outward migration, often mediated by social conflict, violence, regime change, and, in some instances, societal collapse.

In the second part of the analysis, the authors employ a panel data framework using combined climate, migration, and economic data from 154 countries between 1990 and 2020 to quantify the climate-migration relationship. They identify a highly significant, nonlinear association characterized by a U-shaped curve centered around a temperature optimum, with stronger nonlinearities observed in lower-income countries. Despite having experienced smaller average temperature increases to date, tropical countries have seen the highest rates of outward migration, driven by higher baseline temperatures and lower adaptive capacity due to limited economic resources. Using their estimated model, the authors simulate future migration flows under five IPCC emissions scenarios and one tipping-point scenario involving the collapse of the Atlantic Meridional Overturning Circulation (AMOC). Under moderate scenarios, migration increases modestly, but in the most extreme case, outward migration from tropical regions is projected to double. In the AMOC collapse scenario, where northern regions experience severe cooling, total global outward migration could rise from 200 million in 2020 to one billion by 2100, with much of the displacement originating from cold and temperate zones. The authors caution that these estimates may represent a lower bound, given nonlinear dynamics that are difficult to fully capture and the likely economic losses from climate damages, which would further constrain adaptive capacity.

In summary, the papers in this volume underscore the importance of adopting an integrated, multidisciplinary approach to address the risks posed by climate change and the degradation of ecosystem services. The seven research papers and two keynote lectures collectively demonstrate that fostering technological innovation, incorporating the value of natural capital into decision-making, embedding ecological and climate-related risks into financial oversight, and advancing coordinated policy frameworks are all critical for building resilient and sustainable economic systems. As environmental pressures continue to

intensify, the insights and strategies presented here offer a coherent roadmap for researchers, policymakers, and financial institutions seeking to preserve macroeconomic stability and ecological integrity in the face of accelerating climate change.

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Central Banks and Sustainability: A Comprehensive Review of Green Mandates, Speeches, and Actions*

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In recent years, public attention to environmental issues, particularly climate change, has grown significantly. This increased awareness has prompted both public and private entities to take various actions, with central banks around the world being no exception. In most cases, the initial motivation for central banks to begin integrating environmental concerns into their policies has

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been the financial stability risks posed by environmental factors. However, as the discourse evolves, there is also an emphasis on how monetary policy should integrate climate change and environmental considerations. This paper aims to examine the various ways central banks are addressing these issues.

Our study explores central banks' responses to environmental challenges in three key areas: the integration of environmental issues into central bank mandates, the discourse among central bankers on this topic, and the practical actions central banks have taken in this realm. We accomplish this by thoroughly reviewing the formal mandates, public discourses, and practical actions of numerous central banks. We begin by compiling the official mandates of 125 central banks (123 countries and two monetary unions), classifying them based on their approach to climate-related risks and support for mitigation and adaptation policies, and analyzing how these differences relate to various country-level factors. Next, we analyze the timing and content of 290 speeches addressing climate change issues from 24 central banks (including those of G20 countries), conducting a Topic Modeling Analysis (TMA) to scrutinize the prevalent themes in these speeches. Finally, we examine the "green" actions implemented by central banks in two ways: first, by analyzing the specific topics covered by 361 green papers from 44 central banks and, second, by documenting and classifying various activities and initiatives undertaken by 125 central banks, for which we compute a bank-specific "greenscore" metric to measure the extent of their involvement in diverse environmentally conscious initiatives.

Our main findings can be summarized as follows: Firstly, central banks are progressively incorporating environmental themes into their mandates, either explicitly or implicitly, often aligning their policies with the guidelines provided by national governments or supranational organizations. An outstanding example is the case of the central banks within the European Union. Secondly, based on our analysis of speeches, we find that central bankers have increasingly addressed environmental issues in their speeches, though since 2022—coinciding with the rise of inflation—these references have notably declined. Thirdly, as we analyze the research conducted by central banks on environmental matters, we find a significant increase in research papers addressing various green topics, which we interpret as indicative of a heightened interest in gaining a deeper understanding of environmental challenges and exploring the potential roles that

central banks can play in addressing them. Finally, our assessment of concrete actions reveals a greater degree of activity among central banks in wealthier and larger countries and identifies a negative correlation between the level of environmental engagement by central banks and certain country characteristics, such as inflation and reliance on natural resources. Additionally, we observe heightened environmental participation in countries with robust democracies and greater exposure to environmental risks. Surprisingly, we find weak or negligible connections between central bank mandates and their environmental initiatives. Furthermore, the level of central bank independence does not appear to significantly influence their environmental actions.

1. Related Literature

Our paper contributes to the literature on green central banking by providing a comprehensive analysis of central banks' roles and actions in the context of environmental issues, offering insights into the evolving nature of monetary policy in the face of global environmental challenges. For our analysis of mandates, we build upon the work of Dikau and Volz (2021). While their study provides a critical examination of central bank mandates in the context of sustainability—emphasizing legal frameworks and policy implications—, our research delves deeper into the practical execution of these mandates. Their analysis, grounded in the 2017 IMF's Central Bank Legislation Database, is updated in our study to include data up to 2023, with a meticulous examination of each central bank's mandate. We follow these authors in classifying banks based on how their mandates "address climate-related risks and support policies for mitigation and adaptation." Our comparative analysis with Dikau and Volz's (2021) data reveals a more nuanced and gradual incorporation of environmental themes into central bank mandates in recent years, particularly among larger and more independent banks. Interestingly, while Dikau and Volz (2021) assert that central banks should integrate climate-related risks into their policy frameworks, our findings suggest that the existence of such mandates does not consistently dictate the banks' proactive engagement in environmental issues.

Our research makes a distinctive contribution to the limited scholarly exploration of the interplay between discourses and climate change. Neszveda and Siket (2023) explore the impact of the

European Central Bank's (ECB) green speeches on stock returns, taking into account the company's performance in emissions reduction. Meanwhile, Arseneau and Osada (2023) investigate the role of mandates in shaping central bank communication on climate change, employing different methodologies to identify speeches addressing this issue. Our work differs from theirs in two main aspects. Firstly, we pre-filter speeches exclusively focused on climate change issues and extend our sample to include 24 central banks. Secondly, we focus on identifying the most critical communication topics and their temporal dynamics, irrespective of mandates or market-impact considerations. We analyze green speeches from central banks employing Natural Language Processing (NLP) techniques to delve into the topics and their temporal evolution. Our study aligns with a growing literature that employs text analysis tools to explore different aspects of central bank documents. This literature includes the correlation between mandates and speech sentiment—Bohl and others (2023)—, studying implicit preferences and objectives of central banks—Shapiro and Wilson (2022)—, and employing NLP to extract signals indicating the health of the economy and financial market—Petropoulos and Siakoulis (2021), Park and others (2023), Ahrens and others (2023), Masawi and others (2014). Similar to our paper, Feldkircher and others (2021), Warin and Sanger (2020), and Carboni and others (2020) also employ text analysis to delve into the messages conveyed and underlying themes of central bank speeches.

In addition, we review the environmental actions reported by central banks on their official websites until November 2023. This review, detailed in Section 4, focuses on: (a) participation in international climate change initiatives (e.g., the Network for Greening the Financial System—NGFS); (b) research, organization, and participation in workshops; (c) development of "green" statistics; and (d) actions to mitigate negative impacts within the banks' internal operations. Based on this information, we introduce a "greenscore" metric in our study, which provides a comprehensive and multidimensional analysis of central banks' responses, encompassing both their actions and discourse. This approach not only extends the discussion initiated by Dikau and Volz (2021) but also sheds new light on the complex interplay between theoretical commitments and practical actions in the domain of green monetary and financial policies. We also use NLP to analyze the core topics in climate change research papers published by central banks. Inspired by works from different branches

of knowledge,[1] our aim is to uncover the five main research themes and track their temporal evolution. The ultimate goal is to examine the mandates of central banks, scrutinize their communications, delve into their research focus, and study the coherence between these actions.

To some extent, this work is conceived as a complementary initiative to the extensive survey conducted by members of the NGFS in the second half of 2022.[2] Published in July 2023, the survey results encompass responses from approximately two-thirds of the NGFS members, exploring areas such as physical impacts, the transition to a net-zero economy, the integration of climate variables into macroeconomic models, and climate considerations in monetary policy operations. Our contribution, in this regard, lies in the analysis of publicly available information extracted from the websites of each central bank. The challenge is twofold: on the one hand, the immense heterogeneity in the ways information on climate change is published meant a meticulous site-by-site search; and, on the other hand, it involves considerable effort in the systematization and organization of the information for subsequent analysis.

The structure of this paper is as follows: Section 2 analyzes environmental issues within central banks' mandates. Section 3 examines central bankers' speeches on this topic. Section 4 explores the actions taken by central banks regarding environmental issues. As a result of this section, we propose the green-score involvement measure to provide a quantitative assessment of features defining a bank's green involvement actions. Finally, Section 5 provides concluding remarks.

2. Mandates: Central Banks' Formal Responsibilities Concerning the Environment

The question of whether central banks should engage in environmental matters is increasingly pertinent. Central banks are generally governed by specific legislation that defines their mandates—the objectives that justify their actions and the main instruments for achieving these goals. Typically, these mandates prioritize inflation control and financial stability. Some argue that fulfilling these primary objectives justifies central banks' involvement

1. See for example Anupriya and Karpagavalli (2015), Sun and Yin (2017), Choi and others (2017), and Cho and others (2017).

2. As of 13 June 2022, the NGFS consisted of 127 members and 20 observers.

in environmental issues due to their potential impact on prices and financial stability. Others believe that central banks' responsibility towards environmental concerns should be explicitly stated in their mandates. This section analyzes the extent to which environmental issues have been formally incorporated into the mandates of monetary authorities.

Our analysis aligns with that of Dikau and Volz (2021), who examine how climate change mitigation and adaptation policies fit within central bank mandates. Utilizing the IMF's Central Bank Legislation Database (2017 version), these authors analyze the mandates of 135 monetary institutions globally,[3] classifying these mandates based on their approach to climate-related risks and support for mitigation and adaptation policies.[4]

Building on this approach, our work updates the categorization of mandates. Unlike Dikau and Volz (2021), who rely on information included in the IMF's database, we conduct our analysis through direct examination of information made publicly available by the central banks on their official websites. We perform an online search for the legal acts or norms governing each central bank, scrutinizing whether they contain references to engagement in climate change, environmental issues, or sustainable development. Based on this analysis, we categorize the mandates as *explicit*, potentially *implicit*, or *none* (non-mandated).

The database for this section includes 125 central banks (123 countries and two monetary unions), comprising 100 banks from the lists in Tables 1 and 2 of Dikau and Volz (2021),[5] and 24 additional central banks selected for their relevance to our analysis.[6]

3. Dikau and Volz (2021) focus much of their analysis on central banks that have neither explicit nor implicit mandates and find that a majority of these are undertaking some form of "green" action, despite not being explicitly mandated to do so. A relatively smaller share of central banks (25%) are neither mandated nor taking any action.

4. Dikau and Volz (2021) identify three types of mandates: explicit, implicit, and none. Within the last group (non-mandated), they differentiate between central banks that continue to address environmental issues (despite not being mandated) and those that do not.

5. It is important to mention that Dikau and Volz (2021) do not identify the 34 central banks in their study that do not have a mandate (explicit or implicit) and are not actively working on environmental issues.

6. Most of the new institutions analyzed are located in the Americas. A detailed comparison of our work with Dikau and Volz (2021) can be found in Appendix A. The specific list of countries covered in Dikau and Volz (2021) and in our sample can be found in the appendix.

2.1 Classification of Central Banks According to Mandates

After reviewing the websites of these central banks, we classify them into three categories according to their mandates, in line with Dikau and Volz (2021):

1. **Explicit Mandate:** Mandates that actively enhance, promote, or support "sustainability" or sustainable development/growth. A notable example is the ECB, which recently reevaluated its secondary mandates to address climate change issues.

2. **Implicit Mandate:** Mandates that underpin the government's economic objectives or policy goals related to environmental sustainability. Generally, following Dikau and Volz (2021), a potentially implicit mandate is seen as support (not just promotion) for the government's general goals, particularly sustainable economic growth. For example, the German Central Bank's website states: "We are factoring in the effects of climate change on price stability and the stability of the financial system."

3. **Non-mandated:** Mandates that do not address sustainability or related policies.

Within the third group, Dikau and Volz (2021) further distinguish between (a) central banks that address environmental issues without a mandate, and (b) those that neither have a mandate nor mention any related actions on their websites. A clear example of subgroup (a) is the Federal Reserve of the United States (Fed), which has stated it lacks a mandate or adequate tools for environmental issues,[7] yet still undertakes actions to understand the phenomenon and its implications.[8] Our analysis indicates that the percentage of central banks in subgroup (b) (6 percent) is much lower than in Dikau and Volz's (2021) sample (25 percent), which suggests an increasing trend towards greater institutional involvement in these issues.

2.1.1 Changes in the Distribution of Central Banks' Mandates

Comparing the information from Dikau and Volz (2021) with our data collected from the official websites of various financial institutions, we observe a noteworthy shift. The number of central

7. See the speeches of Waller (2023), Powell (2023).
8. See Brainard (2021).

banks with explicit environmental mandates increased from 16 (11.9 percent) to 31 (24.8 percent), as shown in Table 1. This increase is particularly prominent among European economies, reflecting their progression in incorporating environmental aspects into their mandates and missions. This trend towards explicit mandates has resulted in a decrease in the number of central banks with implicit mandates, from 53 (39.3 percent) to 44 (35.2 percent), and those without any mandate, from 66 (48.9 percent) to 50 (40 percent).

Additionally, we extend the characterization of unclassified economies in tables 1 and 2 of Dikau and Volz (2021).[9] We assume that unlisted monetary institutions covered numerically in the study do not engage in climate change activities nor have mandates for such. While direct identification of these economies is not feasible, our examination of the sample suggests an under-representation of economies from the Americas. Out of 27 analyzed economies, three have potential implicit mandates for environmental issues, 20 are engaging in related activities despite lacking formal mandates, and only four appear inactive.

Lastly, Table 2 illustrates the distribution and adjustment of a common sample of 100 central banks across both datasets.[10] The data confirms the increase in explicit mandates and a decrease in those with implicit or non-mandated. Notably, there is no regression in institutional commitment, indicating the growing significance of addressing environmental concerns within central bank policies.

Table 1. Central Banks by Mandate in Each Database

	2020		*2023*	
	N	%	*N*	%
None	66	48.9	50	40.0
Implicit	53	39.3	44	35.2
Explicit	16	11.9	31	24.8
Total	135	100	125	100

Source: Authors' calculations.
Notes: Number and percentage of central banks in each category. "2020" is the estimated statistical closure date for the database by Dikau and Volz (2021). "2023" refers to our database.

9. We are unable to precisely identify the full list of institutions reviewed by Dikau and Volz (2021). Some economies are missing from the list provided in their paper to match the total N of the analysis. Therefore, to enable a more accurate comparison, we have also compiled a sample of countries that align between their database and ours. Table 2 illustrates this match.

10. See footnote 9 for details.

Table 2. Distribution of Central Banks in Both Samples

		2023			
		Explicit	*Implicit*	*None*	
	Explicit	16			16
2020	Implicit	15	38		53
	None		4	27	31
		31	42	27	100

Source: Authors' calculations.
Notes: Distribution of central banks that are present in both databases. "2020" is the estimated statistical closure date for the database by Dikau & Volz (2021). "2023" refers to our database.
Interpretation: From the 53 central banks with an implicit mandate in 2020, we find that in 2023, 15 of them had an explicit mandate, while the remaining 38 kept an implicit one.

2.1.2 Exploring Mandate Determinants

What factors contribute to the differences in mandates among countries? This question, while important, is challenging to answer and extends beyond the strict scope of our research. Nevertheless, in this section, we attempt to identify some determinants (or correlates) of green-related mandates.

First, we explore how mandates are related to various factors that could potentially influence them. Table 3 compares groups of central banks by mandate type (none, implicit, explicit) in terms of population, income, inflation, and the economy's dependence on natural resources.[11] As discussed later in Section 4.4, where we analyze the determinants of central banks' green actions, there are reasons to believe that differences in these socioeconomic variables could influence how green issues are addressed by mandates.

As shown in Table 3, there are significant differences in the population size, income levels, and inflation rates of countries based on the type of central bank mandate. Comparing the median of each group, it is evident that central banks with explicit mandates generally belong to countries with larger populations, while those with implicit mandates are smaller. Regarding income, the implicit mandate group is wealthier, with the median country nearly doubling the per capita income of the non-mandated counterpart. In terms of inflation, the explicit mandate group stands out, with a median inflation rate exceeding that of the other two groups by one percentage point. Finally, economies with implicit mandates tend to be less dependent on natural resources, though the differences are not highly significant.

11. The annual average for each country from 2015 to 2022 is considered for each variable.

Table 3. Mandates and Economic and Demographic Indicators

	Population		*Income*		*Inflation*		*Nat. Res. Rents*	
	Avg.	*Med*	*Avg.*	*Med*	*Avg.*	*Med*	*Avg.*	*Med*
None	85.9	9.6	24.0	15.8	5.0	2.7	3.6	1.4
Implicit	25.9	7.1	30.5	28.5	4.0	2.7	2.8	0.7
Explicit	39.5	13.1	28.1	26.4	9.3	3.7	3.7	1.1

Source: Authors' calculations and World Development Indicators (WDI).
Notes: Avg. and median values of population size, per capita income (in 2017 USD PPP), inflation rate, and natural resource rents (as a percentage of GDP), for countries categorized by central bank mandates.

Econometric Analysis of Central Banks' Mandates

We now conduct a more formal analysis of the determinants of central bank mandates. For this purpose, we run a series of multinomial logistic regressions, where the dependent variable is the categorical variable "mandate", taking values "none", "implicit", and "explicit". As explanatory variables, we include the four socio-economic variables already mentioned, as well as three additional institutional and environmental variables. Details on the variables included in the regressions and the sample are presented and discussed in sections 4.4 and 4.5.

Table 4 presents the corresponding regression results. The outcomes for the "implicit" and "explicit" mandate categories of the dependent variable are reported, with the "none" (non-mandated) category as the reference (not reported). Thus, the coefficients for "implicit" and "explicit" indicate the change in the log odds of a central bank having either an implicit or explicit mandate as compared to having non-mandated, holding all other variables constant. The first regression (columns (1.1) and (1.2)) suggests that the four variables discussed above (income, population, inflation, and natural resource rents) are not very relevant to the probability that a central bank has an explicit, implicit, or non-mandated. The coefficients are generally not significant, with the only exception being the size of the population, which tends to decrease the probability of having an implicit mandate.

In a second regression (reported in columns (2.1) and (2.2)), three institutional and environmental variables are added: the Democracy index, produced by the Economist Intelligence Unit, Romelli (2022)'s Central Bank Independence Extended (CBIE) index, and the index of risk exposure to extreme natural events by *The World Risk Report 2023*. The results now suggest a very significant effect of the degree of

central bank independence, which positively impacts the probability of shifting to an implicit mandate and, especially, to an explicit one.[12] At the same time, an increase in exposure to the risk of extreme natural events decreases the probability of having both an implicit and an explicit mandate.

Table 4. Mandate's Determinants

	Multinomial Logistic Regressions			
Mandate	*Implicit*	*Explicit*	*Implicit*	*Explicit*
(Ref.: Non-mandated)	*(1.1)*	*(1.2)*	*(2.1)*	*(2.2)*
Per capita Income	-0.234	0.179	-0.039	0.265
	(0.324)	(0.377)	(0.366)	(0.506)
Population	-0.279*	-0.08	0.31	0.636**
	(0.149)	(0.155)	(0.243)	(0.282)
Rents from Nat. Res.	-0.473	-0.269	-0.466	-0.062
	(0.298)	(0.353)	(0.360)	(0.419)
Inflation	-0.227	0.419	-0.461	0.228
	(0.403)	(0.380)	(0.459)	(0.449)
Democracy Index			-0.151	-0.012
			(0.203)	(0.204)
CB Independence			3.542**	5.379***
			(1.672)	(2.056)
Risk Exposure			-0.991***	-1.145**
			(0.369)	(0.456)
Constant	3.836	-2.270	0.687	-7
	(3.706)	(4.202)	(4.066)	(5.715)
Observations	101	101	101	101
Pseudo R-squared	0.048		0.166	
Log PL	-102.9		-90.2	

Source: Authors' calculations.
Notes: Robust standart errors in parentheses. (*** $p<0.01$, ** $p<0.05$, * $p<0.1$). Log PL: Log pseudolikelihood. The table presents results from multinominal logistic regressions where the dependent variable is the central bank's environmental mandate: none, implicit, or explicit, with "none" serving as the omitted reference category. Coefficients indicate the change in log-odds of having either an "implicit" or "explicit" mandate relative to "none" for a one-unit increase in the predictor variable.

12. An increase of one standard deviation in the CBIE multiplies by 1.8 the probability of shifting to an implicit mandate, and by 2.5 the probability of shifting to an explicit mandate.

As a partial conclusion from this analysis, these preliminary results suggest that the inclusion (implicit or explicit) of environmental responsibilities in the mandates of central banks does not seem to respond as much to economic or environmental factors but rather may reflect institutional or political aspects. However, as will be seen later in Section 4.5, these changes in the probability of having one mandate or another do not necessarily impact the concrete actions that central banks end up carrying out in response to environmental challenges.

3. Speeches: Central Banks' Discourse on Environmental Issues

In this section, we examine 290 speeches addressing climate change issues delivered by central banks affiliated with the G20, including the ECB. The sample covers the period from 2015 to September 2023. Our analysis has two main objectives: (i) to provide a comprehensive overview of the quantity and temporal distribution of these speeches, and (ii) to conduct a TMA to scrutinize the prevalent themes in these speeches. This entails exploring the recurrent topics, their relative relevance, and how these themes have evolved over time.[13]

3.1 A Temporal Perspective of Central Bank Speeches on Climate Change

Figure 1 presents the evolution of quarterly speeches related to climate change by G20 central banks, including the ECB. Two aspects of this progression are particularly notable. First, there has been an increasing trend in the frequency of speeches. Despite exhibiting significant volatility, this trend becomes more discernible after applying seasonal adjustments. Second, the peak in the volume of speeches occurs in Q4 2021, followed by a decline that coincides with the period of heightened inflation, which may have influenced the central banks' communication focus. Nonetheless, as further

13. The sample exclusively encompasses speeches addressing climate issues written in English from a total of 24 central banks. See the list in Appendix C. The data collection process involved exploring the climate change section on the respective central bank's website. In cases where the website lacked a dedicated section for these topics, a thematic search was conducted through the site's search engine. Additionally, we performed a search through the Bank for International Settlements (BIS) speech repository, a platform that consolidates speeches from central banks on various subjects, directly provided by the banks themselves.

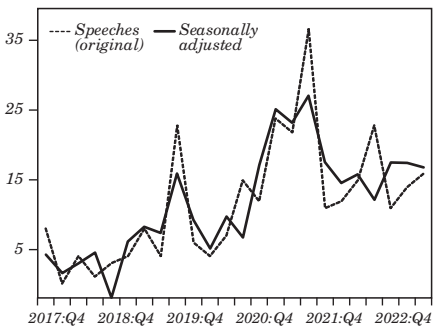
explored in subsequent sections, the volume of research papers and other climate-related initiatives by these central banks continued to grow during this period.

3.2 An Overview of Topic Modeling Analysis

Topic modeling is a suite of algorithms frequently utilized in machine learning and NLP to identify abstract topics within a corpus of documents. These statistical models aim to reveal latent semantic structures embedded in textual data. Topics are conceived as clusters of terms that frequently co-occur across documents, suggesting a shared semantic domain. The underlying premise is that documents focusing on a particular topic will feature related words more prominently than those centered on different topics.

In NLP, the concept of n-grams—a contiguous sequence of n words—is particularly salient. For instance, a unigram refers to a single word, e.g., "economy"; a bigram, to a pair of consecutive words, e.g., "economic policy"; and a trigram, to a sequence of three words, e.g., "federal economic policy". N-gram models predict the probability of the last word in the sequence based on the preceding words.

Figure 1. Central Bank Speeches Related to Environmental Issues



Source: Authors' calculations.
Notes: Speeches delivered each quarter by central bankers from G20 countries, including the ECB. Includes speeches published online in English from Q4 2017 to Q3 2023. Seasonal adjustment performed with X-13ARIMA-SEATS. Based on data collected online.

Topic models extend beyond unigram models, which assume that each word is sampled from a common term distribution. Mixture of unigram models posit that a document is associated with a single topic, with all its words emanating from the corresponding term distribution. In contrast, mixed-membership models, such as Latent Dirichlet Allocation (LDA), permit documents to exhibit multiple topics with varying distributions.

Our analysis employs LDA, a Bayesian framework that groups observations into unobserved subgroups, clarifying the observed data's similarities. This approach assumes that each document is a composite of topics, with each topic being a composite of words. For example, in a model with topics on "monetary policy" and "financial markets", words such as "interest", "inflation", or "currency" may dominate the first topic, while "stocks", "bonds", and "trading" may prevail in the second. Significantly terms can be shared across topics; "investment" might feature in both.

The selection of the number of topics, k, must be determined prior to the analysis and is dependent on the corpus' granularity. Too small a k may oversimplify the semantic landscape, while too large a k could result in overlapping or indistinct topics. Although the literature proposes various methods to ascertain the appropriate number of topics, the final decision hinges on the analyst's interpretive judgment, shaped by their expertise, the data's nature, and the specific objectives of the research.

3.3 Topic Modeling Analysis of Central Bank Speeches

In this section, we use TMA to examine the corpus of speeches in our database. Our objective is to unravel the narratives and communication strategies central banks employ concerning climate change and environmental issues. Moreover, this analysis aims to trace the evolution of these discussions, offering insights into the dynamic discourse of central banks on green matters.

3.3.1 Word Cloud of Central Bank Speeches

We applied an LDA model, identifying six distinct topics.[14] Figure 2 presents word clouds for each topic, illustrating their thematic focus.

14. The number of topics, $k = 6$, was selected after conducting several analyses with varying topic counts, ensuring minimal overlap and optimal thematic distinction.

In Topic 1, prominent words like "risk" and "finance" with "scenarios", "transition", and "understand" suggest a focus on financial risk scenarios and their implications. Topic 2 is populated by terms such as "bank", "financi", "system", "institution", "innov", and "regul", indicating discussions around the institutional and regulatory aspects of the financial system. Topic 3 highlights "green", "sustain", "financ", "invest", "sector", and "develop", aligning with green investments and sustainable finance topics. Topic 4 highlights "bank" in conjunction with "risk", "supervisor", "manag", "action", "plan", "report", and "publish", hinting at themes pertaining to risk supervision within banking systems. Topic 5 centers on "price", "inflation", "energy", and "shock", thus suggesting a focus on inflation-related concerns, particularly those arising from shifts in the energy sector. Topic 6 features "polici", "monetary", and "central", reflecting concerns related to Central Bank monetary policy.

3.3.2 Topics in Green Central Bank Speeches

Table 5 provides an overview of the most probable terms within each identified topic, their respective rankings by probability in the overall collection, and a descriptive label that captures the latent thematic structure.

The topic with the highest average occurrence in the entire collection, at 20 percent, is Financial Risk Scenarios. This is closely followed by Green Investments, and Regulation and Innovation in the Financial System, each with probabilities of around 18 percent and 17 percent, respectively. The fourth and fifth spots are occupied by Banking Risk Supervision and Energy-Related Inflation, each with a probability of about 15 percent. The topic of Central Monetary Policy is in the sixth position, holding a probability slightly below 15 percent.

Significantly, the three topics related to financial matters[15] collectively represent a 53.9 percent occurrence probability in the speeches. This underscores a significant emphasis on financial issues in the analyzed speeches. While the primary focus of this document does not specifically center on financial policy issues, it is important to note that, at least at the discourse level, there is a relatively more substantial presence of topics associated with financial aspects. Our objective is to illustrate that, in terms of communication, these topics

15. Specifically, Financial Risk Scenarios, Regulation of the Financial System, and Supervision of Banking Risk.

have centered on risk scenarios, regulatory issues, and themes related to banking supervision.

Figure 2. Most Frequent Terms by Topics in Speeches Related to Environmental Issues

(a) Topic 1

(b) Topic 2

(c) Topic 3

(d) Topic 4

(e) Topic 5

(f) Topic 6

Source: Authors' calculations.

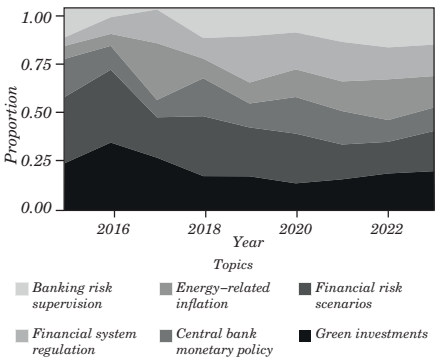
Notes: Word clouds represent the most frequently occurring terms within each of the six identified topics in the analyzed speeches of central bankers. The size of each term in the word clouds corresponds to its relative frequency within the respective topic, visually indicating the prominence of specific terms.

Table 5. Terms and Probabilities of Research Topics in Green Central Bank Speeches

Rank	*Prob*	*Term 1*	*Term 2*	*Term 3*	*Term 4*	*Term 5*	*Latent Structure*
1	0.197	risk	scenario	insur	financi	manag	Financial Risk Scenarios
2	0.178	bank	financi	system	innov	regul	Financial System Regulation
3	0.171	green	financ	sustain	invest	carbon	Green Investments
4	0.164	risk	bank	ngfs	supervisori	manag	Banking Risk Supervision
5	0.150	inflat	price	rate	energi	shock	Energy-Related Inflation
6	0.140	polici	monetari	central	price	bank	Central Bank Monetary Policy

Source: Authors' calculations.
Notes: The table presents the terms, probabilities and ranks associated with topics obtained from the estimation of a Latent Dirichlet Allocation (LDA) topic model (with a k parameter set to six) applied to 290 speeches of a group of G20 Central Banks. The last column includes the likely latent topic structure associated with each topic's terms.

Figure 3. Temporal Evolution of Topics in Central Bank Speeches



Source: Authors' calculations.
Notes: Annual relative proportion of each theme in green speeches produced by central banks between 2015 and 2023.

Temporal Dynamics of Topics in Central Banks' Speeches

The temporal progression of topics is depicted in Figure 3. Notably, the theme of Green Investments initially held significant prominence before 2018 but saw a decline until 2020. This trend reversed post-2020, with Green Investments re-emerging as a predominant theme in central bank communications, especially evident in 2023.

In contrast, the Central Monetary Policy theme shows an inverse pattern. Initially, it had a subdued presence, barring the year 2016. However, from 2018 onwards, it gained increased emphasis until 2020, followed by a gradual decline, making it the least intense topic in 2023.

The focus on energy-related inflationary issues has been ascending in central bank speeches since 2018, peaking in 2022, with a slight decrease in 2023. Notably, this theme was also significantly highlighted in 2017, differing from the earlier years of the analyzed period.

Regarding financial topics, speeches predominantly centered on Financial Risk Scenarios, particularly between 2015 and 2016. While maintaining considerable focus, these discussions gradually shifted towards financial Regulation and Supervision themes. Collectively, these three financial topics—Risk Scenarios, Regulation, and Supervision—make up a substantial part of central bank speeches over time.

In brief, Green Investments and Monetary Policy related to climate change collectively constitute a consistent segment of communication in speeches, comprising close to a third of the relative proportion of topics over time. However, their dynamics since 2018 exhibit a contrary trajectory, marked by a decrease in the Green Investment topic and a corresponding increase in the Central Monetary Policy topic, a pattern that has reversed in the last two years. The broader financial topic occupies nearly half of the relative portion of topics, yet its distribution is heterogeneous over time. The Financial Risk Scenarios topic emerges with the highest intensity; however, starting in 2021, matters related to regulation and, in recent years, financial supervision assume a more prominent role. Finally, Energy-related Inflation demonstrates an escalation in the relative proportion of speeches from 2021 onwards, aligning with the global context of heightened inflation and shocks stemming from geopolitical events.

4. Actions: Central Banks' Initiatives Regarding Environmental Issues

This section examines the specific actions central banks are implementing in response to climate change and related environmental concerns. Our objectives are twofold: first, to identify the range of initiatives undertaken by various central banks, particularly in terms of green research; and second, to devise a central-bank-specific

metric that effectively quantifies these green actions, facilitating a comparative analysis across banks while accounting for factors influencing their environmental engagement.

In line with these goals, the section is structured into two primary segments. The initial segment provides an overview of the primary dimension in which central banks engage with environmental issues: research. The latter segment focuses on evaluating and quantifying the policies and measures central banks have adopted to confront environmental challenges. This analysis leads to the development of a greenscore, which allows for comparisons across central banks. The greenscore encapsulates actions and classifies them into ten distinct categories. Concluding this section, an econometric analysis is conducted to discern the key factors that drive central banks' proactive engagement in environmental matters.

It is important to note that during the information-gathering process for this study, we identified a series of activities and methods employed by central banks in this domain. Each of these actions and research outputs is reported in Appendix D. We encourage readers to refer to this appendix for a better understanding of the genesis of the greenscore.

4.1 Central Bank Green Research

Research constitutes a pivotal area where central banks are integrating green issues into their analytical frameworks. Recognizing that a comprehensive understanding of these emergent topics is vital for the formulation and execution of effective policies, this section delves into the research papers produced by central banks. Central banks' research departments have increasingly focused on producing working papers, particularly regarding climate change. This material forms the core of our discussion in this section.

Our analytical approach is twofold. Initially, we assess the overall volume of literature pertaining to climate change and environmental issues. We trace the evolution of publication frequency over time and its distribution among central banks with different mandates. Additionally, we identify the institutions with the most substantial contributions to this body of work, highlighting the most cited papers within this domain. Following the methodology applied to speeches in Section 3.3, the second phase involves a TMA of paper abstracts. This enables us to elucidate the primary research themes addressed by central banks and track their development over time.

4.1.1 Data and Sample Considerations for Working Papers Analysis

Our analysis focuses on working papers and academic publications related to climate change, primarily published between the 2015 Twenty-first Conference of Parties (COP 21) and August 2023.[16] Our analysis encompasses a subset of central banks previously examined in the mandates analysis,[17] consisting of 44 institutions and a collective total of 361 papers. This selection includes members of the NGFS network alongside additional entities relevant to our study. The complete list of these central banks is provided in Appendix C.

Our manual search process involved a detailed exploration of each central bank's website, focusing on sections dedicated to green and climate change issues. In cases where such specialized segments were absent, we broadened our search to include general research and working papers areas. To enhance our search comprehensiveness, we also employed targeted Google Scholar queries specific to each bank's domain.[18]

For each relevant document identified, we documented its title, abstract, publication year, hyperlink, authors, central bank affiliation, and Google Scholar citation count. When multiple versions of a document were available, we recorded the oldest version and combined citation counts from all versions.

To ensure uniformity and comparability, we included only those publications with English abstracts, such as Spanish-language working papers from the Central Bank of Colombia that have an English abstract. This criterion allowed us to include a broader spectrum of international research while maintaining a consistent approach.

Keywords used in our search included "climate change", "greenhouse gases", "green transition", "adaptation", "renewable energy", "extreme weather", "natural disaster", "carbon emissions", "biodiversity", "Paris Agreement", and "environment".[19]

16. While outside our time range, it is worth noting that some banks engaged in climate research prior to 2015. Examples include the Bank of Nigeria, which published an article about the effects of climate change on its agriculture in 2011 (Apata, 2011), and the Central Bank of Barbados, which presented a paper relating macroeconomic policies and the environment in the Caribbean (Worrell, 1994).

17. See Section 2.

18. We use the "site": operator, for example: ("Climate change" OR green OR sustainable) site: www.snb.ch/en/.

19. Papers that only mentioned these keywords without focusing primarily on climate change-related topics were excluded.

Despite the meticulous nature of our search method, the manual aspect of data retrieval implies that our dataset, while comprehensive, may not encompass every applicable document from the central banks in our study. However, the dataset is representative enough to highlight significant trends and key themes within the central banks' green research initiatives.

4.2 Central Bank Green Research

Research constitutes a pivotal area where central banks are integrating green issues into their analytical frameworks. Recognizing that a comprehensive understanding of these emergent topics is vital for the formulation and execution of effective policies, this section delves into the research papers produced by central banks. Central banks' research departments have increasingly focused on producing working papers, particularly regarding climate change. This material forms the core of our discussion in this section. Our analytical approach is twofold. Initially, we assess the overall volume of literature pertaining to climate change and environmental issues. We trace the evolution of publication frequency over time and its distribution among central banks with different mandates. Additionally, we identify the institutions with the most substantial contributions to this body of work, highlighting the most cited papers within this domain. Following the methodology applied to speeches in Section 3.3, the second phase involves a TMA of paper abstracts. This enables us to elucidate the primary research themes addressed by central banks and track their development over time.

4.2.1 Overview of Green Papers

Figure 4a illustrates the trajectory of working and published papers on environmental topics by central banks in recent years. There is a marked increase beginning in 2019, which gains momentum during the pandemic period. The volume of green research documents increased fivefold from 2019 to 2020 and continued to rise into 2023.[20] This trend is evident across all types of central bank mandates, as shown in Figure 4b. The presence of a specific mandate does not necessarily correlate with the volume of research produced. In fact,

20. The observed decline in the number of papers published (solid line) for 2023 is due to the data collection cutoff in September 2023. The dotted line represents a projection of the total annual output, extrapolated from the documents available up to that point.

central banks with explicit mandates for environmental issues tend to have lower publication counts as compared to those without such mandates.

A detailed examination of central banks with extensive publication records reveals that the top ten are primarily European, including the ECB, along with the U.S. Federal Reserve and its regional entities. The list also features the Reserve Bank of India and *Banco de la República* of Colombia. Combined, these institutions account for nearly 70 percent of the research documents in our sample.[21]

Regarding the impact of this research, 74 percent of the total citations, tallying 4,454, display a temporal distribution similar to the paper counts. The 14 most cited papers, each receiving over 100 citations, collectively accumulate 2,560 references. A preliminary review of the titles suggests that the dominant themes are: the impact of natural disasters and climate extremes (1,018 citations), comprehensive reviews and state-of-the-art surveys (692 citations), financial sector-related issues (497 citations), and stress testing and scenario analysis (353 citations).

The relevance and variety of questions motivating the "green" research agenda at central banks are noteworthy, as evidenced by the diverse range of terms and topics these papers encompass. Several studies focus specifically on the role of central banks in mitigating climate change. They explore why central banks should be concerned about environmental issues and assess potential mitigation strategies.[22] Other studies address climate scenarios and financial stress testing. They construct analytical frameworks to quantify the impacts of climate policy and transition risks, addressing various plausible climate change scenarios. These efforts aim to assess the economy's resilience and adaptability within these contexts.[23]

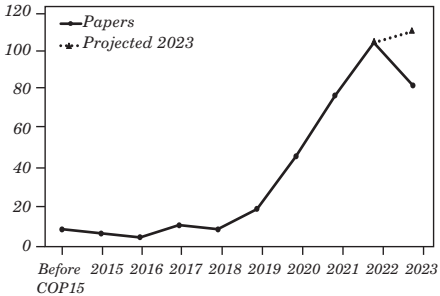
21. Refer to Table C.3 in Appendix C for detailed data.

22. For instance, the work by Arndt and others (2020) highlights the vulnerability of developing economies to climate change and discusses the measures central banks can take to ensure economic stability.

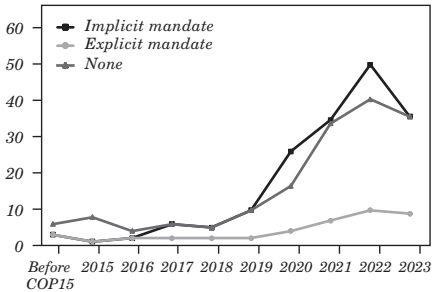
23. For example, Allen and others (2020) propose a framework for France relying on a suite of models, calibrated on the high-level reference scenarios of the NGFS. These scenarios were submitted to a group of voluntary banks and insurance companies to conduct the first bottom-up pilot climate-related risk assessment. In another context, Anvari and others (2022) offer an overview of the modeling frameworks available for assessing climate change impacts in South Africa. This comprehensive examination encompasses both local and global models, providing a thorough understanding of the tools and approaches utilized in assessing the effects of climate change on the region.

Figure 4. Central Bank Papers on Climate Change

(a) Green papers by year



(b) Green papers by mandate and year



Source: Authors' calculations.
Notes: Number of working and published papers addressing climate change or related environmental issues, based on papers with English abstracts published online by a select sample of 44 central banks. The dataset extends up to 2023, with projected figures included for the final year.

In the following section, we provide a more detailed analysis of the variety of topics covered by these papers, offering deeper insight into their content.

4.2.2 Topic Modeling Analysis of Research Abstracts

Venturing deeper into the investigation of central banks' research focuses, we utilize TMA on the abstracts of our research sample.[24] This analysis gauges the prominence of themes and tracks their evolution over time. An LDA topic model with a k parameter set to five was

24. Refer to Section 3.3 for TMA methodology applied to green speeches.

estimated.[25] Just as we did in Section 3, we start by presenting the word cloud for each topic delineated in the analysis.

The word cloud for Topic 1 highlights terms such as "impact", "effect" "disaster", "weather", and "flood". All concepts allude to the Impact of Natural Disasters and the effects of extreme weather events. In Topic 2, the emphasized words include "risk", "financi", "bank", "exposure", "system", and "assess", suggesting a thematic proximity to Exposure Risks within the Banking and Financial System. Topic 3 encompasses terms such as "carbon", "emiss", "energi", "tax", "sector", and "model", collectively encapsulating research related to Carbon Tax Emissions. Topic 4 incorporates terms such as "economi", "polici", "develop", "transit", "global", and "model", indicative of research on Economic Policies for Transition. Finally, Topic 5 is centered around terms like "green", "bond", "market", "firm", "invest", "data", and "environment", whose focus is on investments in the Green Bond Market. Table 6 presents the terms associated with each topic, their probability rankings within the corpus, and a summarizing label for the latent themes.

Table 6. Terms and Probabilities of Research Topics in Central Bank Papers

Rank	*Prob*	*Term 1*	*Term 2*	*Term 3*	*Term 4*	*Term 5*	*Latent Structure*
1	0.247	effect	impact	temperature	disast	flood	Impact of natural disasters
2	0.216	risk	financi	bank	relat	transit	Financial exposure risk
3	0.194	carbon	emiss	energi	tax	sector	Carbon tax emissions
4	0.186	polici	economi	develop	transit	econom	Transition economic policies
5	0.156	green	firm	market	bond	invest	Green bond market

Source: Authors' calculations.
Notes: The table presents the terms, probabilities and ranks associated with topics obtained from the estimation of a Latent Dirichlet Allocation (LDA) topic model (with a k parameter set to six) applied to the abstracts of the 361 green papers in the sample. The last column includes the likely latent topic structure associated with each topic's terms.

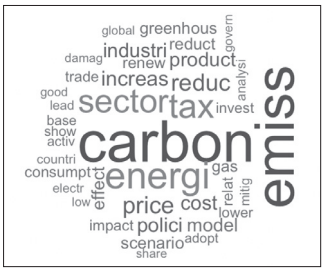
25. Multiple analyses with varying k values were conducted. A $k = 5$ offers a balanced delineation of themes without overlap.

Figure 5. Most Frequent Terms by Topics in Abstracts of Research Papers Related to Environmental Issues

(a) Topic 1

(b) Topic 2

(c) Topic 3



(d) Topic 4

(e) Topic 5

Source: Authors' calculations.

Notes: The *word clouds* display the most frequently occurring terms within each of the five identified topics in the analyzed abstracts of research papers on environmental issues from central banks. The size of each term within the word clouds corresponds to its relative frequency within its respective topic, visually emphasizing the prominence of specific terms.

The probability distribution across the topics is as follows: The Impact of Natural Disasters topic holds a probability of 0.25, indicating an average likelihood of one-quarter presence in each document. The Financial Exposure Risk topic closely follows, with an average

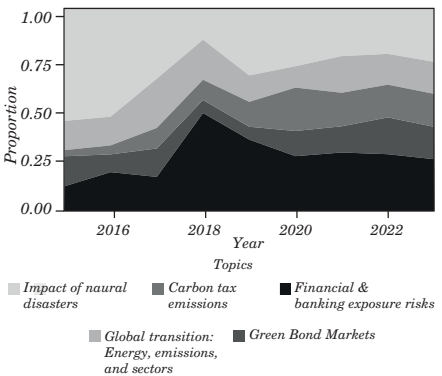
probability of 0.22 within the entire collection. The research topics associated with Carbon Tax Emissions and Transition Economic Policies are both in close proximity, each with a probability of 0.19. Lastly, the topics related to investments in the Green Bond Market are situated not too far behind, with an average probability of 0.16, indicating their likelihood of appearing in the complete collection of documents.

A supplementary method for gauging topic relevance, termed Rank-1, involves determining how often a topic is the most dominant within an abstract. This methodology results in a similar ranking, with slight discrepancies in counts, underscoring the robustness of the identified themes.

4.2.3 Temporal Dynamics of Topics in Green Central Bank Papers

The temporal progression of these topics is depicted in Figure 6, which portrays the annual relative proportion of each theme, indicating shifts in central banks' research focus. The figure elucidates distinct patterns: initial emphasis on Natural Disaster Impact waned after 2017, while research on Financial and Banking Exposure Risk related to Climate Change has surged since 2018. Starting from 2020, there has been an uptick in papers on Carbon Tax Emissions. Meanwhile, the focus on Transition Economic Policies and the Green Bond Market has remained relatively stable, signifying consistent interest since 2015.

Figure 6. Temporal Evolution of Research Topics in Central Bank Papers



Source: Authors' calculations.
Notes: Annual relative proportion of each theme in green papers produced by central banks.

In summary, central banks' climate-related research has predominantly focused on Financial Risk and Natural Disaster Impact, together accounting for nearly half of the identified themes. However, the distribution of these themes has shifted over time, with a recent emphasis on Financial Risk and a decreased focus on Natural Disasters. Other topics such as Carbon Tax Emissions, the Green Bond Market, and Transition Economic Policies have remained steadfast in central banks' research agendas.

4.3 Measuring Central Banks' Green Actions: The Greenscore

Assessing the policies and measures central banks have implemented to address environmental issues poses a notable challenge, primarily due to the difficulty in quantifying these typically qualitative initiatives. This challenge led us to expand upon the work of Barmes and Livingstone (2021), who developed a scorecard to evaluate the "greenness" of G20 central banks and financial supervisors based on their climate change measures. Complementing our extensive analysis of central bank mandates, speeches, and various actions in this paper,[26] we broadened our examination to include "green" policies and measures adopted by 125 central banks. These measures are grouped into ten distinct categories, collectively forming an aggregated indicator that we call the "Greenscore", which is designed to synthesize and quantify central banks' green actions.

The primary aim of the Greenscore is to systematically and clearly represent the contributions of central banks to environmental issues. It facilitates comparative analysis, underscoring the relative engagement of different banks in environmental matters. As a comprehensive metric, the Greenscore encapsulates the wide range and multifaceted nature of green initiatives undertaken by central banks around the world.

4.3.1 Coverage and Selection of Economies

The Greenscore distinguishes itself through its expansive coverage, which includes 125 economies. This extensive inclusion is significant as it provides a comprehensive view of the global central banking

26. See Appendix D for a comprehensive review of actions, activities, and other research outputs in which central banks engage in climate change issues.

landscape in terms of environmental engagement. The criteria for selecting these 125 economies are designed to ensure a sample that is both diverse and representative:

• **Economic Significance**: Priority is given to economies that exert significant economic influence, both on regional and global scales.

• **Geographical Distribution**: A balanced representation from diverse geographical regions is maintained, offering a comprehensive global perspective.

• **Data Availability**: Selection favors economies with accessible and reliable data concerning the environmental actions of central banks, ensuring the Greenscore's accuracy.

• **Diversity of Central Bank Policies**: The inclusion of economies with varied central bank policies and approaches to environmental issues broadens the scope of the Greenscore, capturing a wide array of green initiatives.

4.3.2 Greenscore Methodology

The methodology for computing the Greenscore involved organizing a wide range of central banks' policies and measures into ten distinct areas.[27] These areas are as follows:

1. **Research**: Assesses whether central banks engage in academic research, such as working papers or publications in scientific journals. Detailed in Appendix D.

2. **Reports**: Evaluates the production of documents, speeches, interviews, or press releases by central banks that recognize the significance of climate change on the economy, their related efforts, or progress made. Analyzed in Appendix D.

3. **Education**: Measures educational initiatives addressing climate topics, such as organizing or participating in conferences, workshops, and training sessions.

4. **Statistics**: Checks if central banks compile and disseminate statistical data related to climate change.

27. The process of data collection for the Greenscore was comprehensive and meticulous. It involved a detailed search on the official websites of each central bank, focusing on information available in English and Spanish. This primary search was supplemented with data from the research of Dikau and Volz (2021). Additionally, we expanded our data gathering to include information from reliable sources on the internet. This included reputable local and international institutions, organizations, and media outlets. This broad approach ensured a thorough and diverse collection of data, crucial for accurately assessing the environmental actions and policies of the central banks.

5. **Webpage**: Verifies the presence of a dedicated webpage or section on the central bank's institutional website about sustainability, providing easy access to climate-related materials.

6. **Advocacy**: Identifies central bank participation in organizations that promote sustainability measures, such as the NGFS or the Sustainable Banking and Finance Network.

7. **Monetary Policy**: Includes green policies influencing both directly and indirectly the mechanisms of monetary policy transmission, along with conventional and unconventional policy tools.

8. **Financial Policy**: Encompasses green policies related either directly or indirectly to measures promoting financial stability. For instance, in 2010, the Bank of Lebanon issued a circular to facilitate financing in green sectors by exempting commercial banks from part of the required reserves, thus enabling the financing of these projects at lower costs. Eco-friendly projects include those classified as energy-related and non-energy-related, such as pollution abatement or waste and water treatment. In 2013, the Bank extended a subsidized loan scheme in green sectors by adding a package of USD 331 million.

9. **Leading by Example**: Pertains to institutional commitments and corporate measures undertaken by central banks to lead by example in sustainability. For example, the National Bank of Belgium has undertaken initiatives to quantify and divulge its operational carbon footprint as part of a strategic endeavor to comprehend its environmental impacts. Other central banks, such as De Nederlandsche Bank, have formed dedicated internal committees, like the Sustainable Finance Office, focusing on climate change and Green Finance.

10. **Reserves**: Focuses on the incorporation of green criteria in the management of international reserves. The Central Bank of Brazil, the Central Bank of Norway, the Sveriges Riksbank, and the Central Bank of Trinidad and Tobago have established different frameworks for their international reserve management. These frameworks incorporate sustainability criteria as integral considerations in the processes of counterparty selection and investment decision-making.

For the categories of Monetary Policy, Financial Policy, and Leading by Example, we further distinguish between policies of low, medium, and high impact levels. Similarly, for Advocacy, we categorize measures as low and medium levels. The remaining categories are grouped into a singular level of impact. The detailed classifications and descriptions of each variable used in constructing the Greenscore can be found in Table B.1 in Appendix B.

4.3.3 Greenscore Scoring Methodology

The Greenscore methodology deviates from that of Barmes and Livingstone (2021), who aggregate the total number of measures implemented within each category. Instead, the Greenscore employs a binary scoring system (0 or 1) for each category and its corresponding impact level. A score of 1 is assigned if the central bank has implemented at least one of the policies or measures in that category and impact level, while a score of 0 indicates the absence of such measures.

This binary scoring approach is favored for a couple of key reasons. Firstly, it is less time-consuming, a crucial consideration given the extensive scope of our study, which covers six times the number of economies analyzed by Barmes and Livingstone (2021).[28] Secondly, this method helps to mitigate the natural tendency of central banks in larger or more affluent countries to implement a broader array of measures, attributable to economies of scale in their operations.[29]

4.3.4 Greenscore Computation

The Greenscore is computed by assigning distinct weights to each of the ten categories and their corresponding impact levels. As indicated in Table 7, measures related to monetary policy, financial policy, and reserve management collectively constitute 60 percent of the index. This allocation underscores the significant macroeconomic impact of these measures. Additionally, within these categories, the high-impact measures exert the most substantial influence on the Greenscore.

28. However, there is a possibility that some measures might have been overlooked during the data collection phase. This could be due to the sheer volume of information to process, low visibility of certain activities, language barriers (information not available in English or Spanish), or cases where details of different measures were not distinctly reported.

29. A key distinction from the work of Barmes and Livingstone (2021) is our reclassification of various policies within categories, aiming to more directly reflect those policies that clearly fall within monetary and financial policy frameworks. Furthermore, we have redefined some items within different impact levels for the four corresponding categories, based on the expected impact of the measure. This evaluation considers two aspects: (i) the policy tools available to central banks and their scope to achieve objectives; and (ii) the policy's impact on underlying financial flows. Table B.2 lists the general types of policies and measures within each category by impact level.

Table 7. Greenscore Weights and Impact Level Breakdown

Category	*Weight (%)*	*Impact Level Breakdown*
Research	10	
Reports	3	
Education	4	
Statistics	2	
Webpage	1	
Advocacy	5	Low (33.3%), Medium (66.7%)
Monetary Policy	25	Low (10%), Medium (20%), High (60%)
Financial Policy	25	Low (10%), Medium (20%), High (60%)
Leading by Example	15	Low (10%), Medium (20%), High (60%)
Reserves	10	

Source: Authors' calculations.
Notes: Category weights reflect the relative importance of each category in the overall Greenscore. Impact levels within each category are weighted to differentiate the extent of influence each level has withing its category.

Incorporating these elements, the Greenscore provides a simple yet comprehensive framework for assessing, comparing, and ranking the environmental engagements of central banks across a wide spectrum of economies.

4.4 Exploring Greenscore Determinants

With the Greenscore as an indicator of central banks' actions regarding environmental issues, we now analyze how this metric correlates with other observable institutional, demographic, socio-economic, and environmental indicators at both the country and central bank levels.

4.4.1 Greenscore and Mandates

We first examine the extent to which central banks' mandates[30] are related to their actions. Table 8 shows the average and median Greenscores for groups of central banks with different types of mandates. Central banks with explicit mandates have a significantly higher average Greenscore than others, while no significant differences

30. See Section 2.

are observed between banks with non-mandated and those with implicit ones. This correlation is consistent with the importance that Dikau and Volz (2021) assign to the need for central banks to have explicit goals concerning climate change to advance concrete actions to address it. However, our econometric results, as discussed later in the document, contradict these correlations, suggesting a more nuanced relationship between central bank mandates and their actual engagement with environmental issues.

Table 8. Greenscore and Mandates Breakdown

Mandate	*N*	*Avg.*	*Median*
None	54	20.5	18.1
Implicit	45	21.2	17.0
Explicit	26	25.5	25.1

Source: Authors' calculations.
Notes: Average and median greenscore values across central bank mandate categories.

Table 9. Average and Median Greenscores across Various Economic and Demographic Indicators by Central Bank Mandate Type

	Population		*Income*		*Inflation*		*Nats. Res. Rents*	
	Avg.	*Med*	*Avg.*	*Med*	*Avg.*	*Med*	*Avg.*	*Med*
Low	19.9	19.9	15.6	11.1	31.4	29.3	32.3	31.7
Medium	22.4	22.3	23.3	20.9	22.6	22.7	22.1	22.2
High	30.7	34	34.2	35.5	18.6	13.2	18.2	13.7

Source: Authors' calculations and World Development Indicators (WDI).
Notes: The table presents average (Avg.) and median greenscore values for countries, categorized into terciles. These terciles are based on the average from 2015 to 2022 of four key indicators: population size, per capita income (in 2017 USD PPP), inflation rate, and natural resource rents as a percentage of GDP.

4.4.2 Greenscore and Demographic and Economic Indicators

While the observed correlation between Greenscores and explicit central bank mandates might suggest a direct link, it's crucial to acknowledge the possibility of this correlation being influenced by other socio-economic and demographic factors. Our analysis therefore includes examining the relationships between Greenscores and various indicators that might affect central banks' environmental actions. Particularly, we hypothesize that central banks from larger economies, marked by substantial population sizes or higher per capita incomes, are likely to be more active in environmental issues. This hypothesis aligns with the concept of economies of scale in monetary and financial policy design and implementation, allowing bigger central banks the flexibility to allocate additional resources to secondary objectives like environmental concerns.

In Table 9, we document the evidence supporting this hypothesis. Central banks actively involved in environmental matters tend to be from countries with larger populations and higher per capita incomes. This relationship appears to be monotonic in both cases. These correlations are also visible in Figure 7, which presents scatterplots of the Greenscore against various economic indicators. To ensure that these correlations are not solely driven by Eurozone countries, which generally have higher Greenscores, the figure distinguishes Eurozone countries in black and non-Eurozone countries in gray. The analysis reveals that the positive correlation of the Greenscore with population is pronounced for both groups, while the correlation with income is predominantly observed outside the Eurozone.

Another potential determinant of central banks' engagement in environmental issues could be the inflation rate. Given that central banks' primary mandate is typically focused on price stability, it's reasonable to expect that higher inflation rates could pose challenges in justifying a strong emphasis on objectives that, even if explicitly stated, are often viewed as secondary to the primary mandate.[31] An exception to this might be instances where high inflation is a direct consequence of climate change.[32] However, even in such cases, given that the impact of green policies on inflation is likely to be medium

31. As illustrated in Figure 1, the decline in mentions of climate-related topics from late 2021 could correlate with the significant rise in inflation during the same period.

32. Many advocates for active central bank involvement in environmental matters argue that, if left unaddressed, environmental deterioration will inevitably lead to inflationary pressures, compelling central banks to intervene.

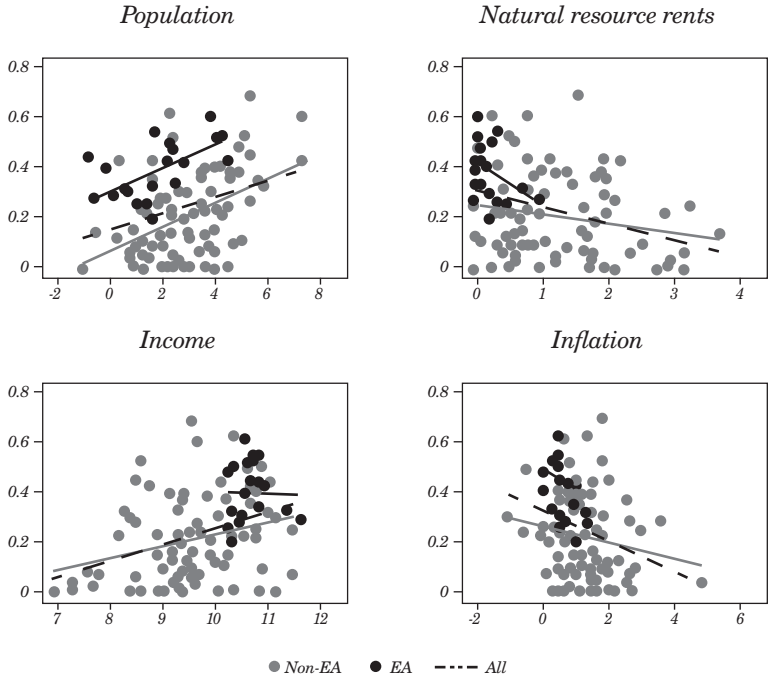
to long-term, central banks might initially focus on addressing the immediate inflationary challenges before re-emphasizing their green policies.

In Table 9, we observe that greenscores tend to be higher in the tercile of countries with the lowest inflation rates in recent years. This score progressively decreases as we move towards terciles with higher inflation rates. This trend is not driven by outliers but is also evident in the median Greenscore of each tercile. The scatterplot of Greenscore against inflation in Figure 7 further clarifies this negative relationship, showing it to be prevalent across all countries, particularly within those of the Eurozone.

Another element that may influence central banks' incentives to integrate environmental initiatives is the economy's dependence on natural resources. The interplay between the Greenscore and a nation's reliance on natural resources offers a multifaceted perspective. Economies heavily reliant on natural resources might prioritize environmental stewardship to guarantee efficient and sustainable utilization of these resources. This prioritization could lead their central banks to enact more proactive environmental policies. However, a counteracting force exists in the short-term incentive to maximize resource extraction, potentially hindering the advancement of green central bank policies.

The data presented in Table 9 indicates a negative correlation between Greenscores and the reliance on natural resources, a trend that intensifies when moving from the second to the highest tercile of natural resource rents as a percentage of GDP. This suggests that economies where natural resource rents constitute a significant portion of the GDP are less active in terms of "green" initiatives. Figure 7 corroborates this finding, showing a negative association between Greenscores and natural resource dependence in both Eurozone and non-Eurozone countries.

Figure 7. Greenscore Correlations with Key Demographic and Economic Indicators



Source: Authors' calculations.

Notes: This figure presents scatterplots illustrating the relationship between the Greenscore (vertical axis) and various socio-economic indicators: population size (in millions), per capita income (PPP USD 2017), annual inflation rate (percentage), and natural resource rents as a percentage of GDP. All variables on the horizontal axis are averages from 2015 to 2022 and are represented in their logarithmic forms to moderate dispersion.

Table 10. Institutional and Environmental Indicators and Greenscore

	Democracy Index		*CB Independence*		*Risk Exposure*	
	Avg.	*Med*	*Avg.*	*Med*	*Avg.*	*Med*
Low	16.5	11.8	23.9	23.3	18.2	13.2
Medium	22.6	21.0	19.5	14.3	21.8	19.6
High	34.0	35.5	29.5	29.8	33.1	35.5

Source: Authors' calculations.

Notes: The table presents average and median greenscore values for countries, categorized into terciles (low, medium, high). These terciles are based on the Democracy Index (Economist Intelligence Unit), the CBIE index of Central Bank Independence (Romelli, 2022), and the index of risk exposure to extreme natural events (The World Risk Report 2023).

4.4.3 Institutional and Environmental Factors Influencing Central Banks' Environmental Actions

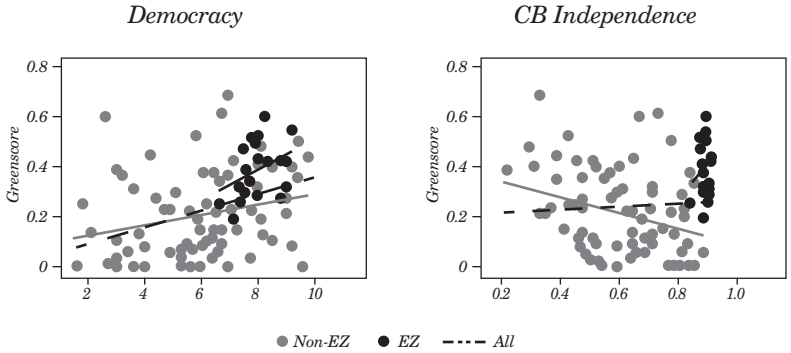
In addition to economic factors, institutional and environmental elements could determine or influence central banks' actions concerning the environment. Here, we examine three such factors: the democracy level of the country, the independence of the central bank, and the country's population exposure to extreme natural events.

Firstly, we assess whether a country's democracy level correlates with how its central banks embrace environmental concerns. There is evidence and arguments suggesting that countries with stronger democracies might be more inclined to embrace environmental policies and rhetoric[33] because democracies often provide more transparent and participatory platforms for environmental policy-making. Democratic governments, accountable to their electorate, might feel more pressure to address environmental issues as public awareness grows. However, there are also counterarguments and many exceptions. Nevertheless, Table 10 suggests a positive relationship between the democracy index of countries and the Greenscore of their central banks. This pattern is marked and consistent across groups with low, medium, and high democracy indices, as well as the average and median democracy index. Figure 8 visually confirms this regularity for both eurozone countries and the rest.

We also analyze the extent to which the degree of independence or autonomy of central banks influences their response to climate change concerns. The answer is not straightforward, as it hinges on how independence interacts with other factors like mandate or level of democracy. For example, central banks with greater independence might possess the discretion to prioritize environmental sustainability within their policy frameworks, but this ultimately depends on their specific mandates and the alignment of environmental issues with their primary objectives. In democratic countries, public and political pressure can influence even independent central banks to address environmental concerns. Furthermore, global, regional, or supranational trends and directives can significantly impact this relationship, exemplified by the central banks in the eurozone. Therefore, the relationship between central bank independence and environmental engagement fundamentally depends on each country's unique economic, political, and environmental context.

33. See, for example, the findings of Bernauer and Koubi (2009).

Figure 8. Greenscore Correlations with Institutional Indicators



Source: Authors' calculations.
Notes: Scatterplots illustrating the relationship between the Greenscore (vertical axis) and the Democracy Index (Economist Intelligence Unit), the CBIE index of Central Bank Independence (Romelli, 2022). Variables on the horizontal axis are averages from 2015 to 2022.

Within our dataset, the overarching relationship between central bank independence and the Greenscore is nonmonotonic, as depicted in Table 10. Nevertheless, upon excluding Eurozone central banks, which uniformly exhibit a high level of independence, a pronounced negative correlation emerges, as illustrated in Figure 8. This trend suggests that central banks with higher degrees of independence tend to be less actively involved in environmental initiatives.

Finally, we assess how central banks' green actions relate to environmental risks, specifically whether exposure to extreme events, such as earthquakes, tsunamis, cyclones, or floods, affects their approach. Table 10 shows that central banks in countries with a larger proportion of the population exposed to environmental disasters generally have a higher Greenscore. That is, they are more active in terms of "green" policy.

4.5 Econometric Analysis of the Greenscore

In the previous section, our focus was on assessing the individual potential of various indicators to explain the environmental actions of central banks. In this section, we expand our analysis to jointly consider the explanatory power of these variables with respect to the Greenscore. We run a series of cross-sectional regressions, with the Greenscore on the left-hand side, and different combinations of

regressors on the right hand side.[34] The variables included in our regressions are presented in Table 11.

Using this approach that simultaneously integrates multiple regressors enables us to more accurately gauge the explanatory strength of each independent variable while effectively controlling for the concurrent effects of other variables.

Table 11. Variables description

Variable	*Type*	*Description*
Greenscore	Dependent variable	Self-constructed index ranging from 0 to 100, representing the extent of environmental engagement by central banks.
Mandate indicators	Independent variable	Classification of central banks as None, Implicit, or Explicit, reflecting the nature of their environmental mandate.
Inflation indicators	Independent variable	Countries are categorized into terciles (low, medium, high) based on their average inflation rate from 2015 to 2022.
Socio-economic controls	Independent variable	Log averages from 2015 to 2022 of: Population size (in millions), Per capita income (in 2017 PPP USD), and Total natural resource rents as a percentage of GDP.
Institutional controls	Independent variable	Two indices: (i) Democracy index, from the Economist Intelligence Unit, and (ii) the CBIE index of Central Bank Independence, as defined in Romelli (2022).
Environmental controls	Independent variable	Two components: (i) Index of risk exposure to extreme natural events (as a percentage of the population), from the WorldRiskReport 2023; (ii) Indicator variables derived from selected components of the index. For each specified risk—tsunamis, riverine floods, and cyclones—countries are categorized into terciles (low, medium, high) based on the proportion of their population exposed.
Eurozone indicator	Independent variable	Dummy variable identifying Eurozone countries.

Source: Authors' research.
Notes: The table presents the dependent and independent variables used in the econometric analysis in the greenscore.

34. We use as regressors the variables described in the preceding section.

4.5.1 Results

The results of our regressions, analyzing the Greenscore against a diverse set of controls, are presented in Table 12. For comparison purposes, all regressions were conducted using a consistent sample of 101 central banks. This sample was selected from the larger set of 125 banks for which the Greenscore was computed, ensuring the availability of all relevant regressors for a robust analysis. The chosen approach facilitates a more uniform and comprehensive understanding of the factors that explain the Greenscore.

We begin our analysis with a specification wherein the mandate serves as the sole explanatory variable, apart from the constant present in all regressions. Column (1) of Table 12 reveals that mandates, when considered in isolation, do not show significant explanatory power with respect to the Greenscore.[35] While the direction of the coefficient signs aligns with our preceding discussion in Section 4.4.1, they do not attain statistical significance.

In Regression (2), we incorporate additional controls for income, population, reliance on natural resources, and inflation. Consistent with the anticipations set forth in Section 4.4.2, a positive correlation emerges between the Greenscore and both a country's income level and population size. The coefficients, significant at the 1-percent level, indicate that a 2.7-fold increase in these variables is associated with an increment of 5.5 points in the Greenscore for income and nearly 5 points for population (from a maximum of 100). Conversely, a similar increase in the proportion of natural resource rents is linked to a 6-point reduction in the Greenscore. Furthermore, the results confirm that central banks in countries experiencing medium and high inflation have a Greenscore 6 to 7 points lower as compared to their low inflation counterparts.

In Regression (3), as detailed in Table 12, we further incorporate institutional and environmental controls. With these additions, per capita income's influence marginally diminishes, while inflation (both medium and high levels) emerges as a more robust predictor of the Greenscore. Consistent with the observations in Section 4.4.3, a higher degree of democracy is found to correlate positively with the Greenscore, exhibiting a statistically significant coefficient at the 5-percent level. However, it is noteworthy that neither central bank independence nor risk exposure to environmental hazards exerts a discernible impact on the Greenscore.

35. In all regressions, only results for implicit and explicit mandates are reported, relative to the excluded base category "None".

Table 12. Greenscore's Determinants

	(1)	(2)	(3)	(4)	(5)
I(Implicit Mand.)	-1.50	-2.03	-0.47	-2.95	-4.43
	(4.14)	(3.53)	(3.80)	(3.64)	(3.36)
I(Exp. Mand.)	1.33	1.27	2.74	0.12	-2.94
	(4.31)	(3.50)	(3.91)	(3.88)	(3.68)
Per capita Income		5.53***	3.22*	3.61*	2.46
		(1.76)	(1.76)	(1.93)	(1.85)
Population		4.73***	4.36***	2.51**	2.98***
		(0.95)	(1.26)	(1.17)	(1.11)
Democracy Index			2.3**	2.25**	1.89*
			(1.04)	(1.07)	(1.03)
Nat. Res. Rents		-5.98***	-4.29**	-4.17**	-3.16*
		(1.82)	(1.88)	(1.87)	(1.87)
CB Independence			-1.32	-1.38	-17.1*
			(9.79)	(9.19)	(8.98)
Inflation					
Medium		-7.25**	-8.77**	-5.64	-3.28
		(3.61)	(3.57)	(3.71)	(3.41)
High		-6.31	-7.32*	-6.62*	-5.22
		(3.95)	(3.89)	(3.64)	(3.32)
Risk exposure			1.26		
			(1.85)		
Tsunamis					
Low				5.31	4.24
				(3.41)	(3.26)
Medium				11.5**	8.96**
				(4.62)	(4.13)
High				8.67	8.13
				(4.36)	(4.07)

Table 12. Greenscore's Determinants (continued)

	(1)	(2)	(3)	(4)	(5)
Riverine Flood					
Low				-1.23	-2.37
				(5.38)	(4.70)
Medium				2.74	1.46
				(5.76)	(5.15)
High				17.6***	13.9**
				(6.56)	(6.31)
Cyclones					
Low				0.274	-0.639
				(5.17)	(4.73)
Medium				-13.60**	-12.40**
				(5.86)	(5.82)
High				-7.1	-6.83
				(5.20)	(5.01)
I (Eurozone)					
Constant	24.6***	-31.4	-25.2	-30.4	-8.91
	(2.70)	(20.40)	(19.90)	(19.80)	(19.60)
Observations	101	101	101	101	101
Adj. *R*-squared	-0.016	0.385	0.405	0.494	0.551

Source: Authors' calculations.
Notes: Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Intrigued by the apparent irrelevance of environmental risk exposure as a determinant of the Greenscore, Regression (4) delves into the specific risks constituting the aggregated index, as detailed in *The World Risk Report 2023*. From our analysis of the index's sub-indices (not reported here), we present only those risk categories that are relevant in explaining the Greenscore, namely, tsunamis, riverine floods, and cyclones. These are introduced as dummy variables indicating low, medium, and high-risk levels, with the base categories (countries with no such risks) not reported. The results reveal that countries with significant portions of their population facing tsunami risks tend to have a higher Greenscore, similar to those with high

riverine-flood risks. Conversely, central banks in countries exposed to cyclones exhibit lower Greenscore levels, a finding for which we currently lack a clear explanation. Regarding the other variables, the influence of inflation is somewhat diminished (with smaller coefficients and reduced significance), while the coefficient for population size decreases in magnitude but remains highly significant. This specific approach, which disaggregates environmental risks, results in a notable enhancement of the model's explanatory power. This improvement is clearly reflected in the increased adjusted R-squared statistics, indicating that environmental risks are a significant driver of central banks' actions. This finding underscores the importance of considering detailed environmental risk factors in understanding the dynamics behind central banks' environmental engagements. Summarizing, our econometric analysis confirms that central banks' mandates are not determinative for their environmental actions. In contrast, factors such as the country's size and income, the level of inflation, and dependence on natural resources are influential. The Greenscore tends to be higher in more democratic countries and, perhaps paradoxically, also in central banks with lesser degrees of independence. It's crucial to consider specific environmental risks, which significantly enhances the explanatory power of our model. Lastly, the results are not driven by the inclusion of Eurozone central banks.

5. Concluding Remarks

This paper employs a comprehensive mixed-methods approach to examine how central banks have incorporated climate concerns into their operations. Firstly, it scrutinizes the mandates of each central bank, assessing whether these legal frameworks act as constraints or incentives for environmental actions. Secondly, it analyzes central banks' speeches to uncover key topics and their evolution over time. Thirdly, the study explores central banks' actions regarding environmental issues: it analyzes research documents on climate issues to understand how central banks focus on climate change and introduces the Greenscore, a green action index that ranks climate actions and facilitates quantitative analysis of central banks' roles in addressing climate change. This multifaceted approach provides a nuanced understanding of central banks' engagement with environmental challenges.

Our analysis reveals a gradual integration of environmental themes into central bank mandates, especially among larger and more

independent banks. While the presence of such mandates does not always lead to proactive environmental engagement, there is a clear pattern of increased focus on climate-related issues in speeches and research outputs. Financial risk and the impact of natural disasters have been predominant research themes, with a recent shift towards financial risk and away from natural disasters.

The quantitative analysis using the Greenscore indicates that factors such as the country's size, income, inflation level, and dependence on natural resources significantly influence central banks' environmental actions. The Greenscore is higher in more democratic countries and, interestingly, in central banks with lesser degrees of independence. Specific environmental risks, such as tsunamis and floods, also enhance the explanatory power of our model.

In summary, there is a growing consensus on the engagement of central banks in environmental issues. More central banks are incorporating this role into their mandates, communicating, conducting research, and taking concrete actions within their operational frameworks. Recent research efforts are focused on understanding and mitigating the impacts of climate change, forming a foundation for new initiatives and policies.

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Appendices

Appendix A: Comparison with Dikau and Volz (2021)

Table A.1. Comparison of our work on mandates with Dikau and Volz (2021)

Dikau & Volz (2021)	*Our work*
Analysis Year: Before 2020	**Analysis Year:** 2023
Original dataset year is 2017.	- Information compiled until the end of September 2023.
Sample: 135 central banks.	**Sample:** 125 central banks.
- Includes 126 institutions and 4 monetary unions. Adds 9 entities not in the IMF database.	- Includes 101 central banks identified in Dikau & Volz (2021) (excludes 34 central banks not identified in their paper).
	- Represents 70% of all central banks and covers more than 95% of global GDP.
Classification of CBs by Mandate:	**Classification of CBs by Mandate:**
- Explicit (Direct), Implicit (Indirect), None.	- Similar to Dikau & Volz (2021).
Sources:	**Sources:**
- Utilizes the IMF Central Bank Legislation Database (based on 2017).	- We review mandates from the original statutory law and official websites.
- Green mandates from IMF Database and other sources.	- Green activities extracted from Dikau & Volz (2021), bank websites, and other reports.
- Central bank websites for updates.	

Appendix B: Greenscore

B.1 Codebook for Greenscore Categories

Research Indicates whether the central bank has conducted research on climate change.

1: Conducted research on the topic.

0: No research on the topic.

Reports Reflects the publication of reports, speeches, interviews, or press releases on climate action or related central bank activities.

1: Issued at least one relevant publication.

0: No relevant publications issued.

Education Promotes educational measures, training sessions, or conference participation/organization on environmental topics.

1: Engaged in at least one educational activity.

0: No educational activities.

Statistics Develops statistics related to climate change.

1: Produced climate-related statistics.

0: No climate-related statistics produced.

Web Presence Maintains a webpage or section on institutional website addressing sustainable development or climate change.

1: Has dedicated online content on the topic.

0: No dedicated online content on the topic.

Advocacy (Low Impact) Engages in low-impact environmental advocacy.

1: Active in low-impact advocacy.

0: Inactive in low-impact advocacy.

Advocacy (Medium Impact) Engages in medium-impact environmental advocacy.

1: Active in medium-impact advocacy.

0: Inactive in medium-impact advocacy.

Monetary Policy (Low Impact) Implements low-impact monetary policies related to environmental concerns.

1: Implemented at least one low-impact policy.

0: No low-impact policies implemented.

Monetary Policy (Medium Impact) Implements medium-impact monetary policies related to environmental concerns.

1: Implemented at least one medium-impact policy.

0: No medium-impact policies implemented.

Monetary Policy (High Impact) Implements high-impact monetary policies related to environmental concerns.

1: Implemented at least one high-impact policy.

0: No high-impact policies implemented.

Fiscal Policy (Low Impact) Executes low-impact fiscal policies targeting environmental issues.

1: Enforced at least one low-impact fiscal policy.

0: No low-impact fiscal policies enforced.

Fiscal Policy (Medium Impact) Executes medium-impact fiscal policies targeting environmental issues.

1: Enforced at least one medium-impact fiscal policy.

0: No medium-impact fiscal policies enforced.

Fiscal Policy (High Impact) Executes high-impact fiscal policies targeting environmental issues.

1: Enforced at least one high-impact fiscal policy.

0: No high-impact fiscal policies enforced.

Leading by Example (Low Impact) Adopts low-impact policies demonstrating environmental leadership.

1: Demonstrated leadership with at least one low-impact policy.

0: No low-impact leadership policies demonstrated.

Leading by Example (Medium Impact) Adopts medium-impact policies demonstrating environmental leadership.

1: Demonstrated leadership with at least one medium-impact policy.

0: No medium-impact leadership policies demonstrated.

Leading by Example (High Impact) Adopts high-impact policies demonstrating environmental leadership.

1: Demonstrated leadership with at least one high-impact policy.

0: No high-impact leadership policies demonstrated.

Reserves Management Incorporates environmental considerations into the management of international reserves.

1: Includes environmental considerations in reserve management.

0: No environmental considerations in reserve management.

B.2 List of Scoring Policies by Impact Level

Advocacy

Level 1: Membership in any relevant international organization related to sustainable economics, other than the NGFS.

Level 2: Membership in the NGFS.

Monetary Policy

Level 1:

• Developing action plans to incorporate climate change considerations into monetary policy implementation.

• Mandatory disclosure of climate-related risks for companies eligible for asset purchase programs.

Level 2: Incorporation of green assets in collateral frameworks.

Level 3:

• Lower interest rates for green loans in financing and refinancing schemes.

• Reduced reserve requirements for green loans.

• Monetary Policy portfolio investments in green bonds.

• Higher interest rates on loans for fossil-fuel-related activities.

• Increased reserve requirements for fossil-fuel assets.

• Monetary Policy portfolio investments exclude or limit investment in fossil-fuel-related activities.

• International reserve management includes sustainability criteria for counterparty selection and investment choices.

Financial Policy

Level 1:

• Publishing guidelines on integrating sustainable finance and developing sustainable financial products.

• Publishing guidelines on incorporating and managing environmental risks.

• Integrating climate risks in regulatory and supervisory expectations, as well as macroeconomic and financial stability assessments.

• Surveys on sustainable finance, climate risks, or climate change.

• Credit schemes including default caused by climate-related events.

• Publishing guidelines for loan programs to sustainable sectors.

• Publishing guidelines for incorporating investments in green bonds.

• Publishing a framework for issuing bonds indexed to climate change indicators.

• Technical support for issuing sovereign green bonds.

Level 2:

• Mandatory disclosure of environmental risks for financial institutions.

• Requirement for financial institutions to incorporate environmental risks into risk management processes.

• System-wide stress testing exercises incorporating environmental risks.

• Incorporating environmental considerations in supervisory review processes.

• Including environmental measures in business outlook assessments.

• Establishing subsidized loan plans for ecological sectors.

• Establishing incentives for investing in environmentally friendly projects.

Level 3:

• Requirement for financial institutions to publish credible zero-carbon goals or carbon emission reduction plans.

• Establishing climate requirements and risk checks that companies must meet for banks to grant loans.

• Requirement for banks to allocate a percentage of sustainable financing to green financing.

• Obligation to implement environmental risk management systems.

Leading by Example

Level 1:

• Measuring and/or disclosing their own carbon footprint in their operations.

• Reducing the carbon footprint in cash production.

• Installing solar panels on their buildings.

• Training courses on adopting climate-related sustainable policies for bank's staff.

• Disclosing environmental risks in monetary and nonmonetary portfolios.

• Disclosing greenhouse gas (GHG) emissions of nonmonetary policy portfolios (NMPP).

• Disclosing climate-related financial information about their NMPP.

• Adopting guiding principles for sustainable finance.

• Voluntary agreements with other entities to promote sustainable finance.

• Sustainable institution certification.

• Commitments made as an institution to address climate change, including a commitment to exclude carbon investments in the future.

• Defining action plans to incorporate climate change considerations into nonmonetary policy application.

Level 2:

• Specialized climate change team.

• Implementation of an internal committee.

• Employee participation in inter-institutional climate-related working groups.

Level 3:

• Investments in green assets from the NMPP.

• Issuance of green bonds in the NMPP.

• Investments in portfolios that include sustainability criteria.

Reserve Management

Level 1: International reserve management includes sustainability criteria for counterparty selection and investment choices.

Appendix C: List of Central Banks for Text Analysis

Table C.1. Number of Speeches by Central Bank

N	*Central Bank*	#
1	European Central Bank	57
2	Deutsche Bundesbank	37
3	Bank of England	34
4	Banque de France	24
5	The Riksbank	19
6	Federal Reserve Board	19
7	Banca D'Italia	18
8	Reserve Bank of India	13
9	Bank of Japan	12
10	Banco de Portugal	9
11	People's Bank of China	9
12	Reserve Bank of Australia	8
13	Bank of Canada	8
14	Banco de Máxico	8
15	Reserve Bank of New Zealand	5
16	Banque de Luxembourg	2
17	Bank of Albania	1
18	Swiss National Bank	1
19	Banco Central do Brasil	1
20	Bank of Indonesia	1
21	Bank of Korea	1
22	Banco Central de la República Argentina	1
23	South African Reserve Bank	1

Source: Authors' calculations.
Notes: List of Central Banks and the associated number of climate related spechees published in the websited and in the BIS speech repository.

Table C.2. Number of Research Abstracts by Central Bank

N	*Central Bank*	#
1	European Central Bank	40
3	Federal Reserve Bank of San Francisco	23
5	Federal Reserve Board	20
7	Deutsche Bundesbank	17
9	Federal Reserve Bank of Richmond	15
11	Reserve Bank of India	14
13	Federal Reserve Bank of New York	10
15	Danmarks Nationalbank	8
17	Bank of England	7
19	South African Reserve Bank	6
21	Bank of Indonesia	5
23	Reserve Bank of New Zealand	5
25	Federal Reserve Bank of Cleveland	4
27	Banco Central do Brasil	3
29	Bank of Korea	3
31	Federal Reserve Bank of Dallas	3
33	Oesterreichische Nationalbank	3
35	Czech National Bank	2
37	Monetary Authority of Singapore	2
39	Banque de Luxembourg	1
41	Federal Reserve Bank of Minneapolis	1
43	Nepal Rastra Bank	1
2	Banca D'Italia	29
4	De Nederlandsche Bank	22
6	Banque de France	18
8	Banque Nationale de Belgique	17
10	Banco de la República | Colombia	14
12	Federal Reserve Bank of Chicago	10
14	Bank of Japan	8
16	Banco de Portugal	7
18	National Bank of Hungary	7
20	Banco Central de Chile	5

Table C.2. Number of Research Abstracts by Central Bank (continued)

N	*Central Bank*	#
22	Bank of Greece	5
24	Banco de México	4
26	Norges Bank	4
28	Bangko Sentral ng Pilipinas	3
30	Central Bank of Barbados	3
32	Federal Reserve Bank of Kansas City	3
34	Bank of Russia	2
36	Federal Reserve Bank of Atlanta	2
38	Sveriges Riksbank	2
40	Federal Reserve Bank of Boston	1
42	National Bank of Georgia	1
44	Reserve Bank of Fiji	1

Source: Authors' calculations.
Notes: List of Central Banks and the associated number of climate related research paper published in English in their websites.

Table C.3. Top Citation Central Banks

Ranking	*Central Bank*	*# Citation*
1	European Central Bank	853
2	Federal Reserve Bank of Cleveland	621
3	Bank of England	563
4	Banque de France	449
5	Federal Reserve Board	426
6	Federal Reserve Bank of San Francisco	398
7	Federal Reserve Bank of New York	327
8	Banca D'Italia	274
9	De Nederlandsche Bank	272
10	Banque Nationale de Belgique	268
11	Danmarks Nationalbank	234
12	Federal Reserve Bank of Richmond	218
13	Bank of Greece	215
14	Reserve Bank of New Zealand	160
15	National Bank of Hungary	151

Source: Authors' calculations.
Notes: List of most cited Central Banks.

Table C.4. Greenscore and Scorecard Comparative Ranking (G20 Central Banks)

Ranking	*Greenscore (2023)*	*Scorecard (2021)*
1	Brazil	France
2	China	Italy
3	France	Germany
4	Italy	Eurozone
5	Japan	United Kingdom
6	Germany	Brazil
7	India	China
8	United Kingdom	Japan
9	South Korea	Indonesia
10	Eurozone	Canada
11	Canada	Mexico
12	Mexico	India
13	Indonesia	South Korea
14	United States	Russia
15	Saudi Arabia	Australia
16	South Africa	United States
17	Turkiye	Turkiye
18	Australia	South Africa
19	Argentina	Argentina
20	Russia	Saudi Arabia

Source: Authors' calculations.
Notes: The table includes the 20 central banks assessed by the 2022 Scorecard, which include G20 countries and the European Union. A comparison is also made with the relative ranking of the same central banks in the 2023 Greenscore. Chile is in 38th place out of 125.

It can be seen that the central banks of countries that ranked highly in the Scorecard also ranked highly in the Greenscore. However, there is a noticeable change in the specific order of the central banks. In particular, the Greenscore shows that the G20 countries making the most progress in the areas they are addressing are Brazil, which is the highest-ranked country, followed by China, France, Italy, and Japan, respectively.[36]

Appendix D: Research Output and Activities at Central Banks

Central banks, beyond their fundamental role in monetary policy, actively contribute to the climate change discourse through a wide array of research outputs. This includes working papers, reports, academic publications, and contributions to conferences, showcasing the diverse approaches these institutions take towards environmental issues. In this section, we present an overview of the various types of research materials and activities central banks are engaging in relative to environmental topics. We start by examining the reports they have published and the events they partake in, before delving deeply into the analysis of paper production and publication. This latter aspect likely represents the most significant and visibly prominent facet of their research endeavors.

D.1 Reports, Activities, and Other Materials

Our analysis in this section encompasses a selection of 38 national central banks, two supranational banks (the ECB and the Central Bank of West African States), and the 12 regional Federal Reserve Banks. The initial set of 18 central banks was selected based on their explicit mandates addressing climate change impacts as stipulated

36. The differences in scores and rankings between the Greenscore and the Scorecard can be explained by methodological differences in the construction of each indicator, as well as by the progress made on the agenda over the past year. For example, according to the Scorecard, most G20 central banks have implemented a wide range of financial policies, which is also one of the components that contribute most to the overall score. If one considers only whether a central bank has adopted at least one measure for each impact level, as the Greenscore does, then the contribution of financial policy to the total score decreases. Therefore, central banks that implement multiple financial policy measures will score lower in the ranking.

in their charters.[37] The rest were included due to their significant contributions to research on climate change impacts.

Although the type and volume of research output vary widely among these banks, it is notable that almost all have produced at least one report or paper addressing climate change. Of the 40 national and supranational central banks in our sample, only four lacked materials related to climate topics available on their website.

D.1.1 Reports

Among the diverse materials produced by central banks on climate change, economic reports are the most common and varied. More accessible and practical than academic papers, these reports are frequently produced and made available by most of the banks in our sample. Given the variety of these reports, topics related to climate change are addressed in a broad manner.

Climate Impacts in Economic Outlooks

Notably, climate change issues are increasingly being integrated into economic outlook reports. A prime example is the Central Bank of Malaysia, which included a section on Climate Change Risks and Opportunities in its *2019 Annual Report*.[38] The Czech National Bank provides another example, incorporating a discussion on climate change models and inflation in its *2021 Global Economic Outlook*.[39]

Complete Reports

Concurrently, there is a growing trend of reports fully dedicated to climate change risks and effects, or broader sustainability issues. For instance, the Central Bank of the Philippines detailed the impacts of climate change in the country in its *2022 Sustainability Report*, outlining the bank's actions and future plans.[40] Similarly, the Central Bank of Brazil annually assesses environmental, social, and governance (ESG) related risks and opportunities.[41] These reports

37. This group includes the central banks of the Czech Republic, Fiji, Gambia, Georgia, Hungary, Iraq, Malaysia, Nepal, Philippines, Russia, Singapore, South Africa, Tanzania, Ukraine, Zimbabwe, and the Central Bank of West African States.

38. Box in the 2019 Annual Report available at the Central Bank of Malaysia's website.

39. See Motl and others (2021).

40. The report is available at the Central Bank of Philippines' website.

41. *2022 Report on Social, Environmental and Climate-related Risks and Opportunities* available at the Central Bank of Brazil's website.

typically focus on green finance, sustainability, or country-specific climate change exposure.

Guidelines

Central banks are also playing a pivotal role in mitigating financial stability risks by formulating guidelines for key stakeholders, particularly in banking and insurance. These guidelines aim to bolster resilience against environmental risks and provide best practices for risk management. Several banks, including those in Zimbabwe, Tanzania, Nepal, South Africa, and Singapore, have been instrumental in developing these guidelines.[42]

Climate Disclosure

Lastly, central banks are beginning to evaluate their own exposure to climate risks by publishing climate disclosure reports. Prominent examples include the central banks of Germany, Denmark, and England, which have taken significant strides in this area.[43]

D.1.2 Events

Central banks play a pivotal role in fostering research and dialogue through organizing a wide range of events, from internal seminars within research teams to large-scale international conferences. These gatherings provide a platform for central banks to convene diverse stakeholders, including academics, think tanks, private sector representatives, international institutions, and peers from other central banks.

In these events, discussions on climate change have been gaining prominence since 2015, reflecting a heightened consciousness and concern about its implications on financial stability and the broader financial system. The increased focus on these topics demonstrates the evolving role of central banks in addressing the intersection of climate change and financial dynamics.

Internal Seminars and Workshops

Central banks have engaged in the organization of internal seminars and workshops, focusing on the assessment of the risks

42. The reports are available at the websites of the central banks of Zimbabwe, Tanzania, Nepal, South Africa, and Singapore.

43. The climate disclosure reports are available at the websites of the central banks of Germany, Denmark and England.

induced by climate change on a variety of topics. While the format and the scope differ across banks, we observe that the frequency of these workshops is increasing. We notice that some thematic annual workshops can cover climate change for a specific year, as illustrated by the 4th International Capital Flows and Financial Policies Workshop, a joint event of the banks of England, France, Italy, the OECD, and the IMF, which focused on climate change in 2023. On the other hand, some workshops have been created especially to tackle climate change issues. This is the case for workshops organized by the Central Bank of Chile, the Bank of Japan, or the De Nederlandsche Bank (DNB), for example.[44]

Conferences

In the same vein, international conferences follow a similar pattern. With a larger scope and a more diverse audience than for workshops, the conferences gather various researchers, central bankers, and policymakers over specific topics. Again, climate change topics are increasingly represented, and in some cases, lead to the establishment of the conference. Examples include the ESG conference of the Bank of Italy in 2023 or the 2022 Caribbean Economic Forum on Climate Change by the Central Bank of Barbados. Interestingly, climate change topics are selected for being the theme of annual conferences of multiple central banks. This is the case for the De Nederlandsche Bank in 2021 or for the Central Bank of Chile in 2023.[45]

D.1.3 Other material

In addition to formal research outputs, some central banks also produce insightful and educational materials to engage with a broader audience. These resources vary in form. For instance, the ECB produces podcasts aimed at the general public to clarify its role and initiatives. Concerning climate change, the ECB offers a

44. Respectively, the Workshop on "Macroeconomic and Financial Implications of Climate Change" in 2021 by the Central Bank of Chile, the International Research Workshop on "Climate-related Financial Risks: Interactions of Climate Change and the Financial System" in 2021 by the Bank of Japan, and the Workshop on "Central Banking and Green Finance" in 2017 by the De Nederlandsche Bank (DNB).

45. The annual conference of the De Nederlandsche Bank in 2021 was entitled "The Economy in Transition: Efficient and Sustainable Policies to Support Business Dynamism" and the one of the Banco de Chile in 2023 was entitled "Implications of Climate Change and Ecosystem Services Degradation for Macroeconomic and Financial Stability."

podcast discussing climate risks[46] and introducing *climate disclosures*. Similarly, the Bank of England has developed an educational series called *Explainers*, which includes explanations on various economic topics such as climate impacts.[47]

Moreover, some central banks have dedicated specific sections on their websites to the topic of climate change. These sections usually provide an accessible overview of climate-related issues, followed by an outline of the actions undertaken by the banks. Notable examples include the central banks of France, England, Italy, and Greece.[48]

Collaboration with External Actors

Central bank research also promotes cooperation with external actors. Of the papers we analyzed, almost half were co-authored by individuals affiliated with institutions other than the central banks. These collaborations often involve academics, but also include researchers from international institutions like the IMF and the World Bank, as well as other central banks. For instance, Colacito and others (2019), a well-cited paper, is a collaborative work between the Federal Reserve Bank of Richmond, the University of North Carolina at Chapel Hill, and the Inter-American Development Bank.[49] Significantly, collaboration extends to experts from fields outside economics, as seen in papers like Svartzman and others (2021) and Anvari and others (2022), which include co-authors from diverse scientific disciplines.

46. The podcast titled *Being Transparent about Climate Risks* is available at ECB Podcast.

47. Two articles on climate change, *How is the Bank of England Responding to Climate Change?* (Bank of England Explainer) and *Climate Change: What are the Risks to Financial Stability?* (Bank of England Explainer), are available.

48. See the respective webpages of the central banks of France, England, Italy, and Greece.

49. See also Ferrari and Landi (2023), initially published as part of the ECB Working Paper Series (No. 2500), with contributions from the ECB, Harvard Kennedy School of Government, and the Bank of Italy.

The Short-Run Macroeconomics of the Energy Transition: A Review and Directions for Research

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The global transition to a decarbonized energy system will be as consequential as it is necessary to avoid substantial warming. The transition will reshape the global energy sector and fundamentally transform the role of fossil fuel production and use in the economy. These vast changes introduce significant risks for short-run macroeconomic performance, and those risks are increasing as climate change and the energy transition accelerate.

In his seminal speech in 2015, Mark Carney, then Governor of the Bank of England, called for central banks to better prepare for managing the macroeconomic risks of climate change. He categorized those risks as physical, transition, and liquidity risks.

In this paper, we take stock of what we have learned about transition risks nearly ten years on from Carney's (2015) speech. To keep this task manageable, we focus on policy risk and geopolitical transition risk. Given the significance of the 2021–2024 inflation episode, we pay particular attention to the inflationary risks of the energy transition. This paper entirely omits physical risks, which we discuss in complementary work.[1]

We reach two main conclusions. First, recent empirical work on the macroeconomic impacts of climate policy suggests that large policies—

1. See Bilal and Stock (2025).

Implications of Climate Change and Ecosystem Services Degradation for Macroeconomic and Financial Stability, edited by Maximilian Auffhammer, Elías Albagli, Sofía Bauducco, and Gonzalo García-Trujillo, Santiago, Chile. © 2025 Central Bank of Chile.

ones that encompass a large segment of emissions and thus economic activity—can have negative consequences for short-run real economic activity; however, this conclusion depends on the nature of the policy. In particular, the policy is benign if it induces a carbon price that is predictable and smooth (a carbon tax) but less benign if the induced carbon price is highly volatile and unpredictable (cap-and-trade). Unlike many macroeconomic shocks, carbon-price shocks are directly observable. Moreover, their macroeconomic impacts are of a magnitude readily handled by monetary policy. More work is warranted to clarify how monetary authorities should respond to carbon-price shocks. Other large energy policies, such as the U.S. Inflation Reduction Act (IRA), which provided large subsidies for low-carbon investments, and green industrial policies, have not yet been the subject of careful empirical evaluation from a macroeconomic perspective. These findings lead to the practical conclusion that large climate policies strive to minimize implicit or explicit carbon-price volatility.

Second, global energy shocks—a leading cause of macroeconomic volatility over the past half-century—are likely to be present well into the future. Even under an aggressive net-zero path, demand for fuels in developed economies and globally is likely to persist for decades. Moreover, the economics of decarbonized fuels are similar to those of unabated fossil fuels (inelastic demand, sluggish supply response, and interconnected prices on global markets). As Bordoff and O'Sullivan (2022) emphasize, the geopolitical shifts brought on by the energy transition could be turbulent. Until the role of fossil fuels in production and consumption falls significantly, geopolitical turbulence could well imply an era of enhanced volatility in international energy prices. Although central banks now have considerable experience addressing fuel-supply shocks, now is the time to improve our understanding of how those supply shocks will evolve as the fuels decarbonize.

The history of macroeconomics is one of surprising events with major consequences: the Great Depression, the oil-price shocks and stagflation of the 1970s, the Global Financial Crisis, the Covid-19 pandemic, and more. With its vast scale and global reach, the energy transition is poised to provide fiscal and monetary policymakers with unexpected consequential developments. Macroeconomists can play a unique role in looking around the corner to identify the connections, through institutions, incentives, and political economy, between energy transition shocks and macroeconomic performance.

Adjacent surveys. There are a number of recent complementary surveys on the macroeconomics of climate change, largely focusing on

longer-run macroeconomics. Bilal and Stock (2025) provide a broad overview of loss and damage, mitigation and adaptation. Fernández-Villaverde and others (2024) review recent developments in stochastic integrated assessment models (IAMs). Desmet and Rossi-Hansberg (2024) focus on dynamic spatial integrated assessment models. Hassler and others (2024) review recent climate science for economists through the lens of IAMs. Three surveys of damage estimates are Rising and others (2022) and Bastien-Olvera and Moore (2022), who focus on reconciling the large gap between perceived damages among natural scientists and the comparatively small damages estimated by economists, and de Juan Fernández and others (2022), who focus on econometric estimates of damages including in the context of simultaneous causality between activity and temperature. Timilsina (2022) surveys the large literature on carbon taxes, and Blanchard and others (2023) provide a comprehensive organizing framework for the multiplicity of climate policies from an economics perspective. The field of climate finance is growing rapidly—Hong and others (2020) provide an early framing of this nascent field, and Acharya and others (2023) review climate stress tests of financial institutions.

The remainder of this paper is organized as follows. Section 1 reviews the literature on the macroeconomics of energy and climate policy, with a focus on empirical papers. Section 2 turns to the role of global energy-price shocks, both in the 2021–2024 inflationary episode and looking ahead.

1. Survey of the Literature on Energy and Climate Policy Risks for Short-Term Macroeconomics

There is a vast literature on the economics of carbon pricing and energy policies. The empirical literature on their macroeconomic impact, however, is small and recent, and that is the focus of this survey. We begin with carbon pricing and then turn to other climate policies, including subsidies, standards, and green industrial policies.

1.1 Carbon Taxes

For more than one hundred years, fossil fuels have been the primary source of energy globally. While nuclear power and hydropower were alternatives for new nonemitting generation of electricity and biofuels provided a limited and partial alternative for surface transportation, each had constraints that prevented substituting those energy

sources for fossil fuels at scale. Therefore, until recently the main way to lower carbon dioxide emissions was to reduce the demand for energy services and to improve energy efficiency. In this context, it was natural that carbon pricing—which introduces a Pigouvian tax—became the standard device in economists' toolkit to internalize the carbon externality.

Starting with Nordhaus's (1992) Dynamic Integrated Climate-Economy (DICE) model, the conventional approach to modeling the macroeconomic effect of carbon pricing is to use a dynamic model with growth through capital accumulation, potentially with exogenous technical progress. Imposing a carbon tax increases the price of energy and shifts the mix of capital, labor, and energy from the privately optimal equilibrium to one that uses less energy and thus is less economically productive. The carbon tax therefore reduces long-run capital accumulation, output, and consumption. Using his DICE model, Nordhaus (1992) showed that the optimal per-ton tax on carbon dioxide emissions equals the monetized net present value of current and future damages inflicted by those emissions, that is, the social cost of carbon (SCC). This approach underpins the more complex computable general equilibrium (CGE) models in, for example, Goulder and Hafstead (2017) and Jorgenson and others (2013).

A typical CGE estimate of the effect of a USD 50 carbon tax is a smooth reduction in GDP by approximately 0.7 percent over six years and approximately 1 percent cumulatively over 15 years, for a 15-year average annual reduction in the GDP growth rate of 0.06 percentage points.[2] Introducing short-run labor market frictions can further reduce employment and activity in the short run as the labor market adjusts to the new growth path.[3] These models typically do not include directed technical change or learning-by-doing.[4]

According to the World Bank Carbon Pricing Dashboard, in 2024, there were 53 national and 40 subnational jurisdictions that had implemented a carbon tax, an emissions trading system, or a crediting mechanism. Given this historical experience, the recent literature has embarked on estimating the macroeconomic effects of carbon taxation and comparing them to structural model estimates.

2. This estimate was computed using the Goulder-Hafstead G3 model as implemented on the Resources for the Future (RFF) website, with per capita lump-sum redistribution of the tax revenues to households, as accessed on 14 May 2024.

3. See Hafstead and Williams (2020).

4. See, for example, Fischer and Newell (2008), Acemoglu and others (2012), and Lemoine (2024).

Most of this recent literature consists of event studies of the emissions effects of carbon taxes.[5] Metcalf and Stock (2023) study the 31 countries participating in the European Union Emissions Trading System (EU-ETS), 15 of which had a carbon tax at some point during 1990–2020. The EU-ETS started in 2005 and, during this data span, it covered stationary point sources (power sector and industrial emissions), while nearly all the carbon taxes instead covered transportation fuels and, in some cases, fuels for heating buildings. A key challenge is identifying the causal effect of the carbon tax either because of potential confounders (for example, the carbon tax might be paired with more comprehensive tax reform, making it difficult to disentangle the two effects) or because of endogenous adoption of a carbon tax by a legislature. Using panel local projections and vector autoregression methods, Metcalf and Stock (2023) identify the effect of a shock to the carbon tax by exploiting the institutional timing requirement that the tax be set in advance and thus cannot be affected by current-period shocks to real economic activity. They find that a carbon tax of USD 40 covering 30 percent of emissions reduces emissions by 4 to 6 percent, consistent with estimates in the literature of price elasticities of fuel demand (which in turn reflects the historical lack of alternatives to fossil fuels for transport). Their main macroeconomic finding is that the carbon tax has essentially no effect on the level of GDP or employment after six years (their longest horizon).

These results contrast with the predictions of conventional structural models discussed above, in which a carbon tax induces inefficient production (relative to the private optimum) and thus a loss in GDP and a slight decrease in employment. The empirical finding is consistent with Conte and others (2023), who find that in a multisector spatial integrated assessment model, a small European carbon tax can increase aggregate European economic activity by shifting activity to higher-productivity nonagricultural sectors, which demonstrates the sensitivity within conventional capital accumulation models to sectoral and trade considerations. More expansively, Finkelstein Shapiro and Metcalf (2023) show that the surprising noneffect could be the result of the carbon tax spurring firm creation and technology adoption.

5. See the survey in Köppl and Schratzenstaller (2022).

1.2 Cap-and-Trade

Cap-and-trade systems are the dual of carbon taxes, in which the quantity of emissions is regulated through a system of emissions allowances; trading the allowances determines the carbon price. In a static model without uncertainty, cap-and-trade and a carbon tax are equivalent, but in reality, they differ in many ways. Perhaps most notably from a macroeconomic perspective, cap-and-trade systems have volatile and at least partially unpredictable carbon prices arising from shocks to energy supply and demand under a prespecified emissions quantity cap, which induces changes in the market-clearing allowance price. For example, in 2020, the EU-ETS allowance price was approximately €20/metric ton CO2, rising to €80-€100 during 2022 and 2023 before falling to less than €60 in January 2024. In principle, this difference in price stability could impact macroeconomic performance in various ways, including the additional difficulty that price variability causes for investment planning by firms and for the conduct of monetary policy by central banks.

Känzig (2023) examines the effect of EU-ETS prices on economic activity in participating countries. As in estimating the effect of a carbon tax, identification of the effect is critical and must address the simultaneity problem that a high allowance price could retard demand, but an unexpected dip in economic performance will weaken the demand for allowances, so the price will fall. Känzig (2023) addresses this issue by using an instrument for ETS price changes, specifically the change in the ETS price around regulatory announcement windows, which he then uses to estimate the dynamic causal effect by using a structural vector autoregression instrumental variable (SVAR-IV) method. He estimates a substantial negative effect of the ETS price on economic activity, with higher energy prices leading to a decline in income, consumption, and investment. The magnitude of the effect is large, with an ETS shock that increases the harmonized index of consumer prices (HICP) by one percentage point, leading to an increase in the unemployment rate by 0.2 percentage points, and a decline in industrial production of nearly one percent, after two years. These large macroeconomic effects contrast with prior estimates of the ETS price on firm-level performance, which find little evidence of widespread negative effects on regulated firms,[6] although those studies typically treated the ETS price as exogenous and firm-level

6. See Verde (2020) and Colmer and others (2025).

effects might have been offset by the free allocation of allowances at the outset of the program.[7]

1.3 Carbon Pricing and Inflation

Work on the inflationary impact of carbon pricing is sparse, perhaps because the workhorse calibrated models in the carbon-tax literature (CGEs and IAMs) are strictly real. While an increase in a carbon price, if passed through, will increase the relative price of energy, the effect of that relative price increase on inflation depends on the related questions of whether the central bank accommodates the price increase and whether the relative price increase translates into changes in inflationary expectations.

Konradt and di Mauro (2023) examine the inflationary effects of carbon taxes in the EU and Canada. Their methods and data largely parallel Metcalf and Stock (2023) (extended to include Canada). They find that carbon taxes did indeed increase the relative price of energy but did not change the overall rate of HICP inflation. In contrast, Känzig (2023) finds that a shock to the EU-ETS price acts like a supply shock increasing energy prices and that this increase in energy prices is passed through to overall inflation. This pair of findings is consistent with the results in Moessner (2022), which suggests that ETS prices, but not carbon taxes in EU countries, have an effect on inflation. For EU carbon-tax countries, one explanation for the muted inflation response to a carbon-tax change is that the European Central Bank did not accommodate the country-specific tax change. However, Konradt and di Mauro (2023) also find a muted inflation response for countries, including Canada, with autonomous central banks.

Del Negro and others (2023) introduce a carbon tax into a sectoral New Keynesian model of the United States, in which a carbon tax acts like a negative supply shock and increases the relative price of energy. If the Fed accommodates the tax and prices are sticky, then there is temporary inflation; if it does not, then there is a temporary (small) recession. Coenen and others (2024) echo these findings using the ECB's New Area-Wide Model with an expanded energy sector to model a carbon tax in the EU. Like Del Negro and others (2023), they find that the effects on inflation and output depend on the monetary policy reaction function. Using a New Keynesian model, Ferrari and

7. See Joltreau and Sommerfeld (2019).

Landi (2024) point out that expected future carbon-tax increases can depress current demand, countervailing the direct inflationary effect of a carbon tax.

Hensel and others (2024) use a survey of French manufacturing firms to estimate the effect of changes in carbon prices (the EU-ETS price, identified using the Känzig (2023) shock and estimated using panel local projections) on inflationary expectations. Like Känzig (2023), they find that an ETS price shock increases energy prices and that this shock is passed through to overall inflation; however, unlike Känzig (2023), the effect is short-lived, lasting only six months. Firms' expected inflation correctly increases, then remains elevated for a year—inaccurately, relative to Hensel and others' (2024) estimate of the HICP response, but accurately, relative to Känzig's (2023) longer-lived estimated response.[8]

1.4 Carbon Pricing and Short-Term Macroeconomics: an Assessment

Metcalf and Stock's (2023) benign empirical estimates of a carbon tax on real activity and Konradt and di Mauro's (2023) complementary benign estimates for inflation contrast with Känzig's (2023) strongly contractionary and inflationary effects of the ETS price. These studies arguably have well-identified estimates of the causal effects, the countries and time periods examined in the studies largely overlap, and the magnitudes of the carbon prices are similar for both the tax and ETS price data (generally in the range €15–€100/metric ton). Känzig and Konradt (2023) provide a careful, unified replication of these results, including finding robustness to variations in identification methods, and confirm the discrepancy between benign carbon-tax effects and contractionary and inflationary ETS price effects. Thus, one is left to conclude that these two different carbon pricing mechanisms may indeed have very different effects.

Känzig and Konradt (2023) suggest that four key differences between the EU carbon tax and the EU-ETS are (a) the sectors covered, (b) the different forms of revenue recycling, (c) the spillovers and

8. Konradt and others (2024) find smaller effects of the ETS price on inflation (again using local projections). They do not instrument for the ETS price so it could be that the negative effect found by Känzig (2023) is offset by the positive correlation from a positive demand shock increasing the ETS price, making Konradt and others' (2024) results difficult to interpret.

leakage, and (d) the reaction of monetary policy. We provide some brief observations on these explanations before adding another to the list.

Concerning (a), for most of country-year observations, the EU-ETS covered the power sector and large manufacturing facilities, while the carbon tax covered transportation and (in some countries) home heating. To a first approximation, this means that the consumer experiences the EU-ETS price directly through the price of electricity and experiences the carbon tax through the price of diesel, gasoline, and home heating (mainly natural gas). Both electricity and transportation fuels have numerically similar and small short-run demand elasticities in the range of 0.1–0.4,[9] so, in response to a price increase, the consumption share of the affected product increases, and other consumption shares fall. This suggests that the macroeconomic response to a short-run shock will be similar for electricity and fuels. Also, both have larger long-run elasticities because of adjustment options that take time (buying a more fuel-efficient car, home weatherization, and the like). Thus, from first principles, one would expect to see similar short-run macroeconomic responses to a carbon-price shock emanating from the ETS or a carbon-tax change.

Concerning (b) revenue recycling, Metcalf and Stock (2023) and Känzig and Konradt (2023) find a more negative, albeit noisy, real effect of a carbon tax in nonrevenue recycling countries. As both point out, the identification of the revenue recycling effect is not crisp. For example, the large carbon tax in Sweden was introduced in 1991 as part of a restructuring of the tax code that substantially reduced the marginal income tax rate, which remained at the 1991 level for decades; however, the reform also reduced government's role in society and initiated a long decline in the GDP share of government expenditures.[10] Thus, the initial impact of the carbon tax is, at least for Sweden, confounded by the many other aspects of the reform that go well beyond recycling carbon-tax revenues. On the other hand, subsequent hikes in the carbon tax once it is in place—which comprise most of the variation in the carbon-tax data—are, for Sweden, not linked to subsequent changes in marginal rates[11] and flows into the overall government budget.[12] Notably, Känzig and Konradt (2023) find little difference in HICP response to a carbon-tax hike between revenue recycling and

9. See Table A.5 in EIA (2022). Also see Burke and Abayasekara (2018) and Coglianese and others (2017).

10. See Henrekson and Stenkula (2015).

11. Ibid.

12. See Jonsson and others (2020).

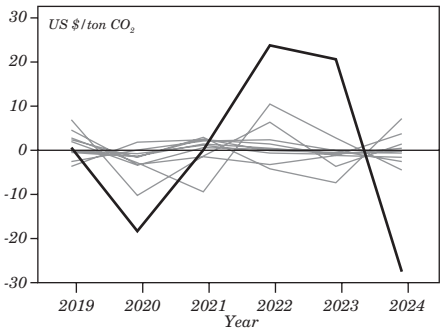
nonrecycling countries, so the differences in the inflationary effects of a carbon price between the two schemes are not explained by how the revenues are used. Thus, while there are differences in real responses between countries based on their revenue recycling schemes, it is difficult to attribute those differences to revenue recycling per se as opposed to treatment effect heterogeneity that happens to be correlated with intended revenue recycling—bearing in mind that the Nordics are four of the six revenue recycling countries.

Concerning (c), leakage is mainly a concern about emissions, not macroeconomic performance. One relevant channel is that European manufacturing, which is covered by the ETS, is disadvantaged in trade by ETS-induced higher energy prices, so an ETS price shock will adversely affect manufacturing employment, all else equal. The other sectors hit by the carbon prices are largely nontraded, for example, transportation services provided within a country. However, as noted above, firm-level studies find little or no negative effects of the ETS on covered manufacturing.

Concerning (d), Känzig and Konradt (2023) present evidence of different short-run interest-rate responses, with the short-run response to a hike in the carbon tax being a drop in the short rate with a slow return to no-change, whereas in response to an ETS price shock, interest rates do not change initially, and then increase for two years before returning to no-change. Thus, the central bank, mainly the ECB, seems to be accommodating carbon-tax increases but leaning against ETS price increases. This begs the question as to why the central bank would respond differently to these two shocks, which both show up in the price of end-use energy. How the central bank should handle carbon-price shocks is a worthy topic of future research.

To this list, we would add (e), the much greater price volatility and unpredictability of the ETS than the carbon tax. As an illustration, Figure 1 shows the deviation from a linear trend of the EU-ETS price and ten major carbon taxes from 2019 to 2024. The standard deviation of the EU-ETS residual is three times the mean standard deviation of the carbon-tax residuals. All else equal, this large variability of the ETS price deters investment in carbon-mitigating technologies. From the perspective of monetary policy, price shocks from the ETS are potentially more difficult for monetary policymakers to address than the predictable price changes from carbon taxes. From the perspective of consumers, volatile energy prices (through a carbon price or otherwise) are also difficult to adjust to because they do not support longer-term planning or investing in energy efficiency. Sorting out the seemingly quite different macroeconomic effects of carbon taxes vs. cap-and-trade is an important issue for macroeconomists.

Figure 1. Deviation of EU-ETS price (black) and Carbon Tax Rates (grey) from Linear Trend, 2019–2024



Source: World Bank Carbon Pricing Dashboard.
Notes: Carbon tax rates (grey) are for British Columbia, Denmark, Finland, France, Iceland, Latvia, Norway, South Africa, Switzerland, and the United Kingdom.

1.5 Climate-Industrial Policy

The Inflation Reduction Act in the United States uses targeted subsidies and tax credits to spur consumer electrification (electric vehicles, heat pumps, etc.), renewable power plants, and investments in manufacturing capacity for energy transition products. This approach is sometimes referred to as green industrial policy because it targets specific technologies and industries. For example, uncurtailed IRA tax credits subsidizing consumer purchases of electric vehicles (EVs) are estimated to cost roughly USD 400 billion through 2032,[13] and the IRA made available a comparable amount of tax credits for new low-carbon electric power generating capacity on the grid. The IRA also included subsidies for manufacturing facilities, and the EV tax credits include requirements for domestic battery production. Although many of the tax credits existed before the IRA, this Act substantially extended their lifetimes, and uptake is projected to be much greater than in the 2010s because the underlying cost of renewables, batteries, and EVs have dropped also substantially. These policies have been augmented separately by tariffs on Chinese EVs and solar panels.

There have been few studies of the macroeconomic consequences of the IRA, its substantial repeal under President Trump, and its green industrial policy features. If there is limited ability to

13. See Cole and others (2023).

substitute clean technology for dirty and absent learning-by-doing, then green subsidies can potentially increase emissions by reducing the overall price of power.[14] With low renewable prices, however, overall emissions reductions can be large and are estimated to be so under the IRA[15]. Bistline, Mehrotra, and Wolfram (2023) develop a structural model with learning-by-doing to evaluate the IRA and suggest that the macroeconomic impact of the IRA is likely to be small. Their analysis includes potential learning-by-doing spillovers created by manufacturing subsidies and domestic content provisions, a core economic argument for industrial policy. They argue that, if the learning-by-doing effect is sufficiently large, the subsidy-plus-domestic-content approach of the IRA can be welfare-enhancing relative to a carbon tax, consistent with Fischer and Newell (2008).

Another aspect of green industrial policy is large tariffs to encourage and protect domestic production. There is a vast literature on the historical effects of tariffs in general, which finds that they reduce welfare and that the price burden falls on the consumer. Additionally, tariffs that focus on green technologies (solar panels, EVs, etc.) drive up costs for low-carbon goods and thus slow the transition to a low-carbon energy system in the importing country. The arrival of the EU Carbon Border Adjustment Mechanism (CBAM) is prompting consideration of carbon border fees in other countries. From a macroeconomic perspective, if those fees are applied mainly to carbon-intensive manufactured imports, as is done in the EU, then the scope of the border fees is sufficiently small so the macroeconomic impact would be modest.

There is a growing empirical literature on industrial policy.[16] The IRA, with its targeted subsidies and tax credits, will provide the opportunity to empirically assess the macroeconomics of green industrial policy.

1.6 Policy Uncertainty

There is now a large literature on the macroeconomic effects of climate policy uncertainty, and the general finding is that, all else equal, uncertainty retards GDP growth and employment.[17] Gavriilidis

14. See Casey and others (2023).
15. See Bistline and others (2023).
16. See, for example, Juhász and others (2023).
17. See Baker and others (2016).

(2021) constructed a climate policy uncertainty akin to Baker and others' (2016) methods, and it has substantial independent variation controlling for overall policy uncertainty.

At the level of an individual firm, climate policy uncertainty tends to reduce investment by providing an incentive to wait until the uncertainty is resolved. Using data on Chinese firms in the mining, manufacturing, and energy sectors, Ren and others (2022) find that an increase in climate policy uncertainty reduces firm-level total factor productivity. Chen (2025) finds that policy uncertainty, through potential expiration of tax credits, adversely affects the timing and amount of investment in the U.S. wind industry.

At a macroeconomic level, because climate policy affects energy prices directly and because exogenous energy-price movements have direct impacts on economic activity, climate policy uncertainty could have a different macroeconomic impact than general economic policy uncertainty.[18] Empirically, Gavriilidis and others (2024) find that controlling for general economic policy uncertainty, climate policy uncertainty retards real activity, with one channel operating through energy prices. A potential channel for climate policy uncertainty to affect economic activity is through asset prices and financial stress.[19] Bauer and others (2023) examine this channel via an event study of the IRA, which during the legislative process had large changes in probabilities of passage. They find, however, that the magnitude of climate policies—and the fact that much of the energy transition has already been capitalized into the valuation of fossil fuel companies—is too small for this channel to be important macroeconomically. While return swings for focused portfolios exceeded 5 percent over three days for some IRA news events, they find a negligible aggregate effect, in part because the negative abnormal returns for fossil fuel companies were offset by positive abnormal returns by renewable or green companies.

2. Energy Shocks and the Macroeconomy

Shocks to global energy prices have been a major cause of macroeconomic fluctuations since the oil crisis of the 1970s. One might reasonably stet that the transition to a net-zero future based on

18. See Fried and others (2021).

19. See, for example, Engle and others (2020), Semieniuk and others (2022), Bolton and Kacperczyk (2023).

reliable domestic renewable energy offers the opportunity for developed economies to lower their exposure to energy-price fluctuations. This section examines this hypothesis. The section begins by recapitulating the role of energy prices in the 2021–2024 inflationary episode, both as evidenced in the now-vast literature on this episode and through some out-of-sample prediction exercises based on empirical Phillips curves. We then turn to the fundamentals of international fuel markets, how they might evolve under net-zero paths and geopolitical considerations of the energy transition.

2.1 Inflation and the COVID-Ukraine Energy Shocks

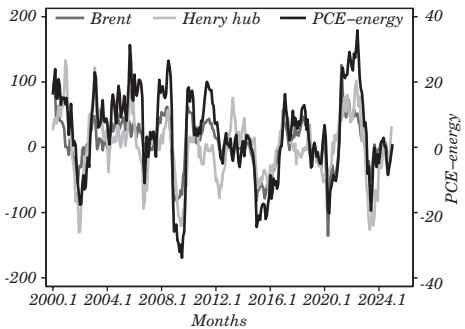
There are now a great many papers on the recent inflation; see Bernanke and Blanchard (2024) and Beaudry, Hou, and Portier (2024) for recent contributions and surveys. Although the quantitative contribution of various factors is still under debate, a common theme is that exogenous energy shocks driven by the war in Ukraine played a key role.

The Russia-Ukraine conflict provides a modern window into the macroeconomic role of energy supply disruptions. Those disruptions began in the late summer of 2021 when Russia did not undertake its normal seasonal refilling of its European gas storage capacity. Starting in June 2022, four months after the invasion, Russia sharply reduced gas supplies to Europe, mainly through the Nord Stream 1 pipeline, and ended Nord Stream 1 flows completely in August 2022. In September 2022, the Nord Stream 1 pipeline was disabled by underwater explosions. Germany's economy was the most directly affected by these curtailments, with German gas supply falling by approximately 20 percent. Moll and others (2024) provide convincing evidence that this large disruption caused surprisingly minor disruptions to aggregate real activity in Germany because of adjustments in demand (reductions by consumers and substitution by industry) and supply (from imports of U.S. liquid natural gas, LNG). The adjustments in demand were driven by extraordinary changes in the price of natural gas. According to the IMF, monthly average European gas prices rose from USD 12.50/mmBtu in July 2021 to USD 41.70 in March 2022, spiking further to USD 70 in August 2022 when Russia suspended Nord Stream 1 shipments. As Europe adjusted both demand and supply—and benefited from two warm winters in a row—prices fell to less than USD 10 in May 2023. These monthly averages mask considerable intramonth volatility, in fact at times

TTF natural gas prompt month futures traded in excess of USD 100. Because oil and gas are substitutes in some industrial applications and in power generation in Asia, and because of heightened uncertainty generally, oil prices also rose, resulting in a large global energy-price shock. This global energy-supply shock also appeared in U.S. gas prices because those prices are tied to international gas prices through LNG exports,[20] with a price decrement for the significant cost of liquefaction, transport, and regasification.

As seen in Figure 2, energy-price inflation in the United States closely tracks inflation in global oil prices (Brent) and in domestic natural gas prices (Henry Hub), and Henry Hub inflation closely tracks Brent inflation since the U.S. began exporting LNG in 2016. This observation and the previous discussion suggest that, for the 2021–2024 episode, it is plausible to treat inflation in PCE-energy as exogenous to the United States over this episode.

Figure 2. Twelve-Month Energy Price Inflation (percent per year) in the United States: Brent Crude Oil and Henry Hub Natural Gas Inflation (left) and PCE-Energy (right)



Sources: U.S. Energy Information Administration and FRED.

20. See Stock and Zaragoza-Watkins (2024).

With this motivation, we conduct an out-of-sample exercise to examine the role of energy prices in U.S. inflation. Specifically, we estimate regressions of the form,

$$\pi_t = \beta_e \pi_t^e + \beta_\chi x_t + \beta \pi_t^{energy} + u_t, \tag{1}$$

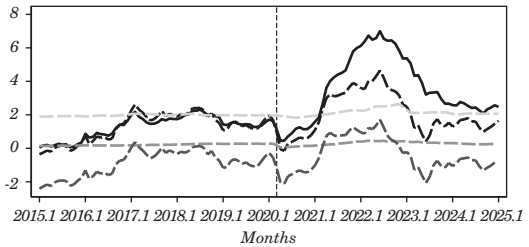
where π_t is the 12-month PCE overall rate of inflation, π_t^e, is expected inflation as measured by the Survey of Professional Forecasters (SPF) forecast of 10-year headline CPI inflation, x_t is the ratio of the vacancy rate to the unemployment rate, and π_t^{energy} is the 12-month rate of inflation of PCE-energy. A constant is included to allow for definitional differences between the dependent variable (PCE) and the SPF forecast (CPI). The main estimation period is January 1984 to December 2019, although we also consider estimation from January 1968 to December 2019. We assess the fit of these specifications over the 2021–2024 inflationary episode by comparing the predicted value of PCE inflation to the actual, where the predicted value is computed by using realized expected inflation, slack, and energy prices. Note that this is an entirely conventional pre-2020 Philips curve specification and does not rely on the many extensions used to fit the recent episode (nonlinearities such as cubics or logs, use of median inflation, use of additional shock variables like measures of supply chain restrictions, etcetera).

Our analysis consists of documenting out-of-sample stability using, separately, only two modifications: the estimation sample and the measure of inflation expectations. The results are summarized in Figure 3, which shows the in- and out-of-sample predicted and actual values from (1) and the decomposition of the predicted value into the three components in — expectations, slack, and energy inflation.

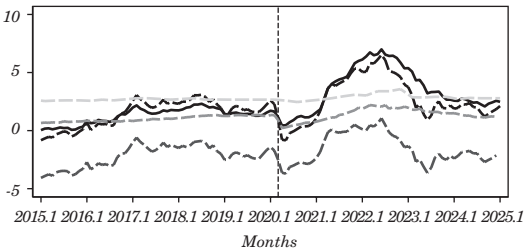
Panel (a) demonstrates the well-known breakdown of the benchmark Philips curve over this episode. Energy inflation explains nearly all the variation in predicted headline inflation, and the model correctly predicted the initial uptick in inflation in 2021. Thereafter, however, the model under-predicted inflation by 2–3 percentage points from mid-2021 through mid-2023. In this specification, the Phillips curve is very flat, with the vacancy-unemployment ratio making a negligible contribution to the predicted value. Because the SPF 10-year expectations are stable (remaining under 3 percent for this full episode), expected inflation also makes only a small contribution to predicted inflation.

Figure 3. Out-of-Sample Philips Curve Decomposition: Predicted and Actual 12-Month Headline PCE Inflation and Contributions of Expected Inflation, Slack (Vacancy-Unemployment Ratio, and PCE-Energy)

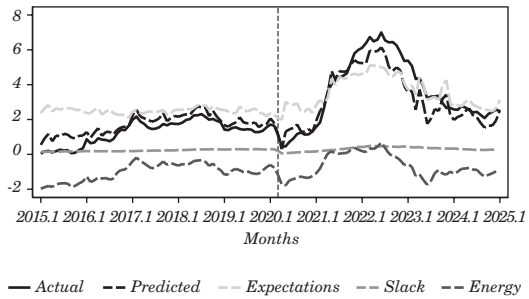
(*a*) *Benchmark: SPF 10-year expectation, estimation 1984-2019*



(*b*) *SPF 10-year expectation, estimation 1968-2019*



(*c*) *Michigan survey 1-year expectation, estimation 1984-2019*



Source: Authors' calculations.

Historically, the episode with the greatest energy-price volatility was the 1970s, a period in which monetary policy initially accommodated the energy-price shocks that led to high headline inflation. Panel (b) therefore re-estimates (1) by extending the start of the estimation sample to January 1968. Using the extended sample has the effect of placing more weight on energy prices and yields a steeper Phillips curve. As a result, the predictions closely track the upswing in inflation and the magnitude of the decline, although the prediction leads the actual decline in inflation by several months.

Panel (c) modifies the benchmark specification by replacing the SPF expected inflation series with the 1-year-ahead CPI inflation expectation from the University of Michigan Survey of Consumers. As stressed by Beaudry, Hou, and Portier (2024), this change substantially improves the performance of the Phillips curve over this episode.

The improvements in panels (b) and (c) are more closely related than they might seem, because Michigan 1-year-ahead expectations are closely related to energy prices, in particular the highly salient gasoline price.[21] In both panels, the change therefore provides more weight to energy prices, either directly (by including the 1970s in the estimation sample) or indirectly (through the Michigan index). Inspection of the contributions of the Michigan index and energy prices in panel (c) indicates that these two contributions are highly correlated, which suggests that it will be difficult to separate a pure expectations effect from a change in expectations induced by energy prices.

Figure 3 thus additional evidence that energy prices played a central role in both the inflation and disinflation of the 2021–2024 period. This role was arguably increased by the Fed initially accommodating the energy-price rise for nearly nine months before raising the Fed Funds rate sharply in the spring of 2022. Although the increase in the Fed Funds rate was insufficient to change the unemployment rate substantially, it did convey intention to sophisticated observers, and the SPF forecast remained under 3 percent. That nuance appears to have been lost, however, on consumers, whose expectations of inflation continued high, 5 percent or more, through November 2022. Whether through their effects on consumers' expectations or through direct passthrough along the supply chain (or both), energy price volatility—which largely stemmed from the geopolitical disruptions due to the conflict in Ukraine—played a numerically dominant role in this inflationary episode.

21. See Coibion and Gorodnichenko (2015).

2.2 Properties of Net-Zero Fuel Markets

One possible consequence of the energy transition is that replacing power generation by fossil fuels with renewable sources, and gasoline and diesel consumption by electrification or low-carbon fuels, will reduce the vulnerability of the economy to fossil fuel price shocks. Here, we provide some largely qualitative comments on the fundamentals of fuel markets that would need to be true for this optimistic view to transpire.

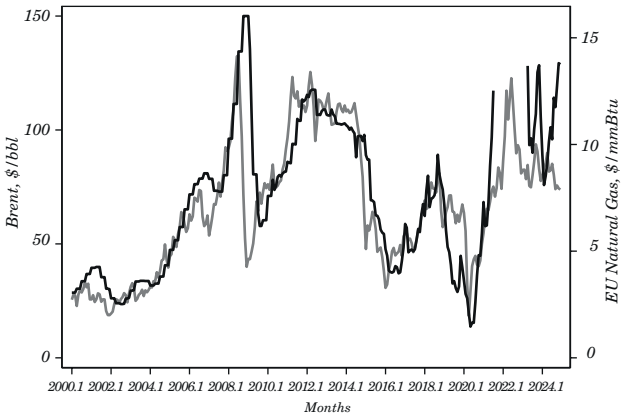
We begin with three observations.

First, prices in fuel markets are internationally determined. This has long been true for oil. Increasingly, with the expansion in trade in LNG, it is increasingly true for natural gas. Moreover, as can be seen in Figure 4, the prices of oil and natural gas are closely linked because they can be (and are) used as substitutes for the production of electricity and for process heat in some parts of the world. In fact, many long-term international LNG contracts are indexed to oil, although the spot prices displayed in Figure 4 are not.[22] Coal prices also fluctuate with oil and gas prices (coal and gas are substitutes in generating electricity), although most coal is sold under long-term contracts.

Second, as discussed in Subsection 1.4, the short-run demand for energy is inelastic. The supply of energy is also inelastic in the short run. The net result is that relatively small disturbances in the supply of or demand for fuels lead to significant price fluctuations.

22. The EU price is a composite price index over the main EU trading hubs (IMF Primary Commodity Prices). Figure 4 omits the EU gas price from August 2021 to March 2023 because the index spiked during that period due to the severe supply disruptions associated with the Russia–Ukraine conflict. The index peaked at USD70/mmBtu in August 2022.

Figure 4. Spot Prices of Natural Gas in the EU (grey) and the Spot Price of Brent Oil (black)



Source: World Bank, FRED.
Notes: The EU gas price is omitted from August 2021 – March 2023 to facilitate plotting.

Third, although the ultimate technology for decarbonizing transportation is uncertain, it is likely that at least some modes of transportation will continue to use liquid fuels. This includes aviation, for which electrification is not expected to be a viable pathway except for low-capacity short-haul flights, marine transportation, and possibly heavy-duty trucking. The current technological options for aviation stress sustainable aviation fuels (SAFs), either low-carbon biofuels or so-called e-fuels, which combine green hydrogen with a low-emissions source of carbon such as direct air capture. Another option is to continue to use petroleum aviation fuel paired with ton-for-ton firm offsets from atmospheric carbon dioxide removal (CDR). For marine applications, currently likely options include green methanol or green ammonia made from green hydrogen, or petroleum marine fuel paired with CDR. For heavy-duty vehicles, the options are electrification, low-carbon biofuels, green hydrogen fuel cells, and diesel with CDR. In all these cases, these fuels are transportable and will compete with each other on price. In the case of aviation, all SAFs are chemically effectively equivalent to petroleum jet fuel ("drop-in" fuels). Because these fuels are substitutes, are transportable, and will be used internationally, we would expect their markets to be linked to oil markets just as natural gas and oil are linked today. Thus, it is reasonable to expect that fuel-price shocks will ripple through the entire fuel market, just as they do today.

These observations suggest that the time scale for the diminishing importance of fuel-price shocks thus depends not on whether those fuels are fossil or green but on the time scale for phasing out fuels altogether. That time scale is highly uncertain. Even for light- and medium-duty vehicles, however, it is measured in decades, not years, because of the slow turnover of the stock of vehicles—the average lifespan of a light-duty vehicle in the United States is more than a decade. For heavy-duty vehicles, the timeframe is longer. As a result, the use of motor gasoline and diesel for light- and medium-duty vehicles is likely to remain high for at least two decades. Taken together, these observations, combined with the inflation of 2021–2024, point towards global energy price fluctuations being a significant driver of overall inflation for decades to come.

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Innovation, Growth, and Environmental Challenges: Schumpeterian Insights into Climate Change and Green Technologies

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I examine how innovation-driven economic growth can be reconciled with urgent environmental challenges through the lens of Schumpeterian economics. I explore the dynamics of creative destruction—the process by which new firms and technologies relentlessly replace old ones—as the engine of growth and consider its implications for decarbonizing the economy.[1] Turning to climate change, we confront the debate over "degrowth" and argue that halting growth is neither a necessary nor an effective solution to environmental crises. Instead, we advocate directed green innovation—deliberately steering technological change toward low-carbon solutions—as the sustainable path forward. I review evidence of path dependence in technology and show how smart policies can redirect inventive effort. I conclude that achieving the green transition requires multiple policy instruments: pricing carbon to internalize environmental costs and green industrial policies (e.g., R&D subsidies, clean technology support) to overcome innovation market failures.

1. Based on my keynote speech at the Central Bank of Chile's Annual Conference in 2023.

Implications of Climate Change and Ecosystem Services Degradation for Macroeconomic and Financial Stability, edited by Maximilian Auffhammer, Elías Albagli, Sofía Bauducco, and Gonzalo García-Trujillo, Santiago, Chile. © 2025 Central Bank of Chile.

1. Background

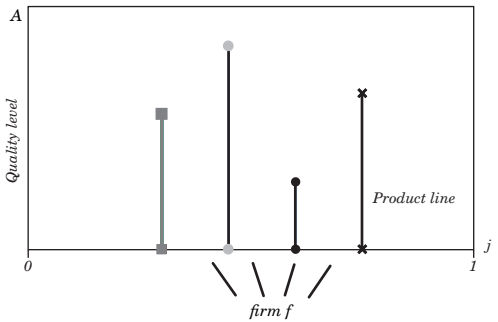
Joseph A. Schumpeter is known for having put forward the notion of creative destruction, i.e., the process where innovations displace old technologies. In his book *Capitalism, Socialism, and Democracy (1942),* he tried to spell out what he meant by creative destruction, but at the time there was no model of Schumpeterian growth. The leading paradigm was the neoclassical model—the Solow model—where growth is primarily driven by capital accumulation, and, under reasonable assumptions of diminishing returns to capital, there can be no long-run growth just by accumulating capital. Solow would point out that technical progress is required to generate long-run growth, but he would not tell you where technical progress comes from.

Peter Howitt and I, in the fall of 1987, noticed this tension and wrote from scratch a model of growth that embodies the notion of Creative Destruction. The model revolves around three main ideas: The first idea is that long-run growth is driven by a cumulative process of innovation where each innovation builds upon previous innovations. The second idea is that innovations result from entrepreneurial activities motivated by the prospect of innovation rents. The third idea is creative destruction: innovations displace old technologies. Innovations make all existing technologies obsolete.

However, the Schumpeterian paradigm reveals a fundamental contradiction. On the one hand, we need monopoly rents to induce innovative activities. On the other hand, yesterday's innovators are tempted to use those rents to prevent subsequent innovation because they do not want themselves to be subject to creative destruction. Thus, regulating capitalism is largely about how to manage this contradictory fact.

This new Schumpeterian paradigm also changed the landscape. First, it gives center stage to cross-firm heterogeneity—between incumbents and entrants, between leaders and followers, between small firms and large firms. In previous growth models, there was no sense of the notion of these kinds of heterogeneities. The model Peter Howitt and I developed was the first framework to capture these dimensions of firm heterogeneity and put them along with firm dynamics as central to the growth process.

Figure 1. Product-Level Firm Dynamics



Source: Author's own.

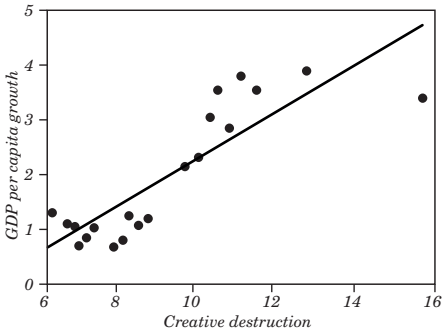
Figure 1 illustrates the firm dynamics in our model, which follows Klette and Kortum (2004), depicting how firms expand or contract based on their success in innovating along different product lines. There is a firm with four lines, each representing a product. The lines are as big as the past innovations that occurred in the product's production process. And, if a firm has that line, it is the only one producing it, with the very best technology to do it. If some firm innovates over the production line of firm *i*, and it is successful, then firm *j* gets to produce that product, extending one line. The firm *i*, on the other hand, loses that product and then loses the line. This model accommodates the expansion and contraction of firms, entry and exit of firms, and emulates the firm size and firm dynamics in a very natural way with the Schumpeterian framework.

1.1 Two Distinctive Predictions of the Schumpeterian Framework

Schumpeterian growth theory yields several distinctive empirical predictions, two of which stand out prominently and have been borne out in data. First, higher rates of creative destruction—measured as job or firm turnover—are associated with higher economic growth. Because growth in this framework results from the constant reallocation of resources to innovative firms, one expects to see a positive correlation between measures of firm turnover and aggregate growth. This is indeed what we observe. Figure 2 shows cross-country

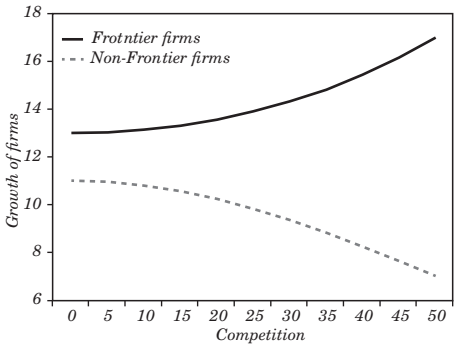
evidence that economies with more vigorous firm entry and exit (or labor reallocation across firms) exhibit higher GDP per capita growth. For example, a country with fluid labor markets and an open environment for startups will likely experience more productivity-enhancing reallocation than one where incumbents are protected, and grow accordingly. Other growth models (e.g., the Solow model or first-generation endogenous growth models without firm heterogeneity) do not generate this prediction.

Figure 2. Correlation of Growth and Creative Destruction



Source: Author's calculations.

Figure 3. Competition, Growth, and Distance to Frontier



Source: Author's calculations.

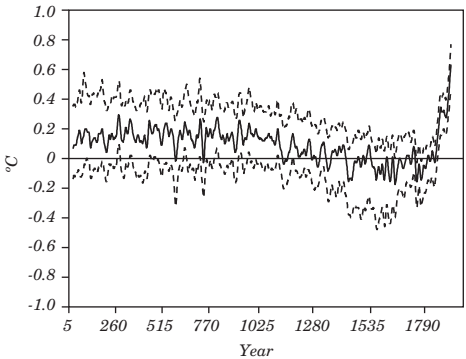
The second prediction from our Schumpeterian model is that more intense competition enhances innovation in frontier firms (leader firms) but discourages it in nonfrontier firms (follower firms). This theoretical prediction arises from two countervailing forces in Schumpeterian models. On one hand, more competition (for example, through lower entry barriers or more rivalrous market conduct) reduces incumbent firms' post-innovation monopoly rents, which could dampen their incentive to invest in R&D—this is sometimes called the "Schumpeterian effect" of competition (Schumpeter himself mused that monopoly profits might nurture innovation). On the other hand, intense competition means a firm cannot take its market position for granted—leading firms under threat will innovate even more aggressively to "escape competition" and widen their technological lead (the "escape-competition effect"), whereas laggard firms might give up because competing head-on with far more advanced rivals yields scant returns. Figure 3 illustrates this prediction. It is produced with UK data, where the solid line shows the frontier firms, the dashed line are the followers, the x-axis is the level of competition (for example, the Lowmary Index), and the y-axis is the growth of the firms (or it could be the innovation rate of firms). If competition increases in intensity, firms that are already at the frontier are capable of fighting back the competition with more innovation since they are already at the frontier. But for follower firms, the cost of getting to the frontier and starting to innovate increases as it is not that profitable anymore, so they tend to grow more slowly.

2. Innovation, Growth, and Climate

In France, we have been arguing with advocates of "degrowth". According to them, the way to fight climate change is to induce negative growth. But, before getting into the discussion, let me show you some facts that motivate their position.

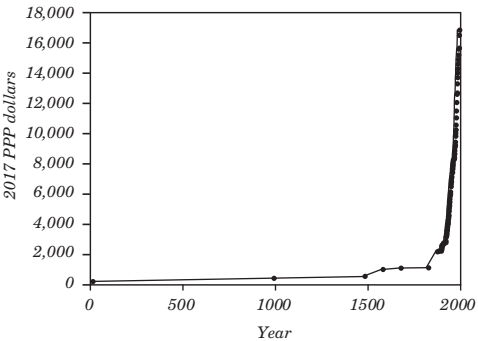
Figure 4 shows that the global temperature remained relatively constant for almost 2000 years, but in the middle of the 19th century, it started to rise sharply at the exact same time as the takeoff of growth, as seen in Figure 5. The similar trajectories in both temperature and product have been understood as evidence that growth led to global warming. Reinforcing this idea, Figure 6 shows that the takeoff of CO_2 emissions of the United States and China occurred precisely at the time when growth took off in both countries.

Figure 4. Changes in Global Surface Temperature Relative to 1850-1900



Source: Gillett and others (2021).

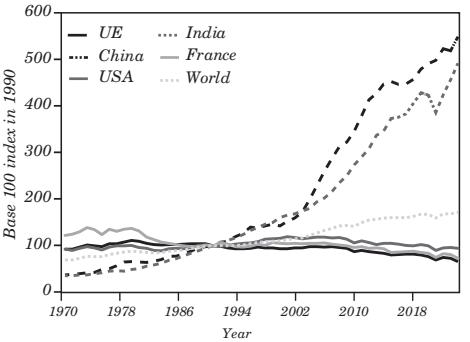
Figure 5. Global Average GDP per Capita over the Long Run



Source: Madison Project Database (2025)

But does this mean that we need negative growth to fight climate change? Of course not. Growth has given a lot to humanity. Also, we have already experienced negative growth with the Covid-19 lockdown, and both output and emissions went down, but at a great cost to society.

Figure 6. Evolution of CO_2 Emissions Worldwide



Source: Based on IEA-EDGAR CO_2 (2024).

The alternative to negative growth is to have green innovations. The alleged conflict between growth and environmental sustainability is not a fundamental incompatibility, but a challenge of managing a technological transition. Degrowth strategies amount to "fighting climate change with one hand tied behind our back," foregoing the very tool—innovation and economic dynamism—that can solve the problem. Rather than shrink the pie, we should change the recipe by which the pie is made. As we will discuss, directing innovation towards green technology allows us to both sustain growth and drastically cut emissions. This requires deliberate action because *laissez-faire* market forces left alone may not achieve it in time. But with the right policies and institutions, green innovation can drive a wedge between GDP growth and carbon emissions. The rest of this presentation focuses on how to bring about this directed technological change for the climate.

2.1 Directed Green Innovation and Path Dependence

Firms do not spontaneously innovate in green technologies. In Aghion and others (2016), we looked at the automobile industry's incentives to innovate in green technologies. Using the World Statistics Patent Data at the European Patent Office over the period 1978–2005, we searched for triadic patents, which are patents registered in the European Patent Office, the U.S. Patent Office, and the Japan Patent Office, and can be considered as patents of good quality. From all this data, they classified the patents between "clean" and "dirty", following

the OECD IPC definition. Something interesting about the database is that you know the history of the patent applicant, meaning that we could track if they patented "green" or "dirty" innovations in the past.

Table 1. International Patent Classification (IPC)

Description	*IPC code*
Clean	
Electric vehicles	
Electric propulsion with power supplied within the vehicle	B60L 11
Electric devices on electrically-propelled vechicles for safety purposes; Monitoring operating variables, e.g. speed, deceleration, power consumption	B60L 3
Methods circuits, or devices for controlling the traction-motor speed of electrically propelled vehicles	B60L 15
Arrangement or mounting of electrical propulsion units	B60K 1
Conjoint control of vehicle sub-units of different type or different functions / including control of electric propulsion units, e.g. motors or generators / including control of energy storage means / for electrical energy, e.g. batteries or capacitors	B60W 10/08,24,26
Hybrid vehicles	
Arrangement or mounting of plural diverse prime-movers for mutual or common propulsion, e.g. hybrid propultion systems comprising electric motors and internal combustion engines	B60K 6
Control systems specially adapted for hybrid vehicles, i.e. vehicles having two or more prime movers of more than on type, e.g. electrical and internal combustions motors, all used for propulsion of the vehicle	B60W 20
Regenerative braking	
Dynamic electric regenerative barking	B60L 7/1
Barking by supplying regenerated power of the prime mover of vehicles comprising engine-driven generators	B60L 7/20
Fuel cells	
Conjoint control of vehicle sub-units of different type or different function: including control of fuel cells	B60W 10/28
Electric propulsion with power supplied within the vehicle -using power supplied from primary cells, secondary cells, or fuel cells	B60L 11/18
Dirty	
Fuel cells: Manufacture thereof	H01M8
Combustion engines	F02 (excl. C/G/K)

Source: OECD.

Table 1 shows the classification of the patents and their classification between "clean" and "dirty" technologies. Using this data, we performed the following estimation:

$$PAT_{CLEAN,it} = exp(\beta_{C,P}\, ln(FP_{it}) + \beta_{C,1} ln(SPILL_{C,it}) + \beta_{C,2}\, ln(SPILL_{D,it})$$

$$+ \beta_{C,3} ln(K_{C,it}) + \beta_{C,4} ln(K_{D,it}) + \beta_{C,w}\, w_{it} + ln(\eta_{C,i}) + T_{C,t}) + u_{C,it}$$

where $PAT_{CLEAN,it}$ is the number of clean triadic patents by firm i in time t, $ln(FP_{it})$ is the fuel price faced by firm i in time t, $SPILL_{X,it}$ is the spillover for innovation of type X, $K_{X,it}$ is the lagged firm's innovation stocks, w_{it} are controls (GDP, GDP/capita, other policies), $\eta_{C,i}$ is a firm-fixed effect, $T_{C,i}$ is a time dummy, and $u_{C,it}$ is a random error. The results are presented in Table 2.

The first result is that, when the fuel price rises, the firm is more likely to innovate clean and less likely to innovate dirty. That is, anything that increases fuel price will tend to redirect innovation from dirty to clean technologies because it becomes less profitable in a market that is shrinking due to the higher fuel price. But the most interesting results come from the stock of clean and dirty patents. Having a higher stock of clean patents increases the propensity to innovate in clean technologies, and having a higher stock of dirty patents increases the propensity to innovate in dirty technologies, thus implying a strong path dependence.

Table 2. Main Results

Variable	*Clean*	*Dirty*
Fuel price	0.886**	-0.644
$ln(FP)$	(0.362)	(0.143)
Clean Spillover	0.266**	-0.058
$SPILL_C$	(0.087)	(0.066)
Dirty Spillover	-0.160*	0.114
$SPILL_D$	(0.097)	(0.081)
Own Stock Clean	0.303***	0.016
K_C	(0.026)	(0.026)
Own Stock Dirty	0.139***	0.542***
K_D	(0.017)	(0.002)
#Observations	68,240	68,240
#Units (firms and individuals)	3,412	3,412

Source: Aghion and others (2016).

Notes: Estimation by Conditional fixed effects (CFX), all regressions include GDP, GDP per capita and time dummies. SE clustered by unit.

This could be bad news: If the economy is operating in *laissez-faire*, the system may get stuck with dirty technologies, on its way to an environmental disaster. The problem is that green innovations do not occur spontaneously. So, there is room for good news: the government can avoid disaster by redirecting innovation towards clean technologies, and early action now can become self-sustaining later due to path dependence.

Now, notice that creative destruction may help in this scenario. Because path dependence is strong, new firms that are entering the market may avoid the problem of transition cost by innovating from the start in clean technologies in a higher proportion than the dirty ones.

Another implication is that we should act now. This is so because, without intervention, innovation is directed towards dirty technologies, thus widening the gap between clean and dirty patent stock. This entails an increase in the cost of intervention that is forcing the firms to move from something they do well (innovating in dirty technologies) towards something they do not have much expertise in (innovating in clean technologies)—in the form of reduced growth as long as clean technologies catch up with dirty technologies.

Table 3 presents the cost of delayed action in terms of consumption estimated by Acemoglu and others (2012) for two scenarios, a ten-year and a twenty-year delay. Measuring the welfare in terms of consumption equivalence, there is a substantial loss from delaying the policies. This is true when we use the discount rate of 1 percent (Stern) and even when we consider a greater discount rate of 1.5 percent (Nordhaus).

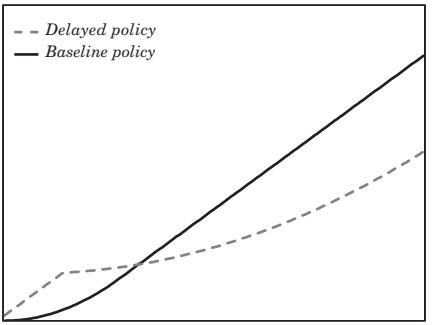
Figure 7 shows the per capita GDP trajectories for these two alternative scenarios. The dashed line corresponds to the delayed policy actions scenarios, while the solid line shows the baseline scenario in which the policy actions are implemented from the beginning. This shows that in the early moments, delaying has a positive impact on GDP because there is no cost of adaptation, but after a few periods, the economy that applied the policies right away surpasses the delayed trajectory.

Table 3. Main Results

Discount rate	*1%*	*1.5%*
Lost consumption, delay of 10 years	5.99%	2.31%
Lost consumption, delay of 20 years	8.31%	2.36%

Source: Acemoglu and others (2012).

Figure 7. Per Capita GDP Trajectories



Source: Author's calculations.

Table 4. Consumption Loss from Using the Carbon Tax as the Only Instrument to Foster Green Innovations

Discount rate	*Lost consumption*
1.0%	1.33%
1.5%	1.55%

Source: Author's calculations.

Another implication of endogenous directed innovation is that we need two instruments because we have two externalities: the environmental one and the knowledge spillovers (path dependence). Thus, another instrument is necessary in addition to the carbon tax to manage the situation. These new instruments are what I call "Green Industrial Policy".

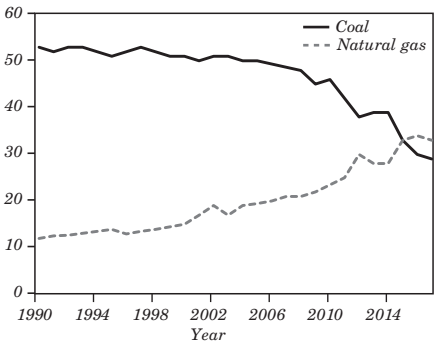
If we only rely on the carbon tax, we will need a higher carbon tax to account for both externalities, which implies a higher loss of welfare. When the discount rate is 1 percent, the consumption loss from using only the carbon tax is about 1.33 percent (as shown in Table 4), with a carbon tax 15 times higher during the first five years and 12 times higher during the following five years.

2.2 Reinforcing the Case for Green Innovation Subsidies

Now, I will introduce an intermediate source of energy (e.g., shale gas). The question that arises naturally in this framework is how

to design the energy transition strategy. The intermediate source is less polluting than coal but more polluting than renewable energy. In Acemoglu and others (2023), we addressed this question using U.S. data.

Figure 8. Share of Coal and Natural Gas in the U.S. Electricity Generation Sector



Source: Acemoglu and others (2023).

Figure 8 shows the share of electricity generation for coal in solid line and natural gas in dashed line, from 1990 to 2016. We see that as natural gas becomes increasingly important, coal decreases its share in the same period. Now, as natural gas is an intermediate source of energy, we analyze the short- and long-run effects of an exogenous improvement in the extraction technology of gas (shale gas boom) on aggregate pollution through the lens of a directed technical change model.

In the short run, abstracting from the innovation effect, there are two opposite effects of the shale gas boom: replacing coal by gas (thus reducing the emissions) and the scale effect triggered by the fact that energy costs are cheaper. Notice that the substitution effect will dominate if gas is sufficiently cleaner than coal.

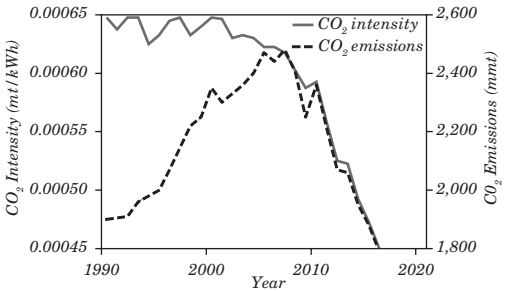
Table 5 shows the results of the calibrated model. Looking at various scenarios of an increase in technology for extracting gas, we can see that there is a fall in CO_2 emission intensity triggered by the substitution effect (first column), but a rise in the total energy consumed, pulled by the scale effect. Overall, we have that CO_2 emissions still go down in the short run. This happens because the reduction of intensity is so big that it more than counteracts the scale effect.

Table 5. Decomposition of Substitution and Scale Effects of the Shale Gas Boom

Total Effects of Improved Shale Extraction Technology B_{s0}			
	%Δ Emission	*%Δ Energy*	*%Δ CO_2*
Baseline parameters			
+10% Increase in B_{s0}	-16.7%	+5.5%	-12.1%
+50% Increase in B_{s0}	-21.0%	+9.6%	-13.4%

Source: Acemoglu and others (2023).

Figure 9. CO_2 Emissions in the U.S. Electricity Generation Sector

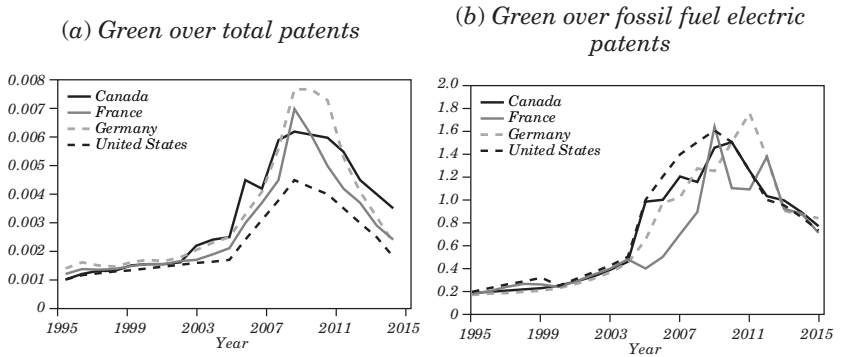


Source: Acemoglu and others (2023).

Figure 9 shows the evolution of CO_2 emissions and intensity in the United States. On the one hand, the intensity was more or less constant until the shale gas revolution and then it fell quickly. On the other hand, the CO_2 emissions were increasing up to the shale gas revolution and then started to decrease. So, at least in the short run, emissions have decreased.

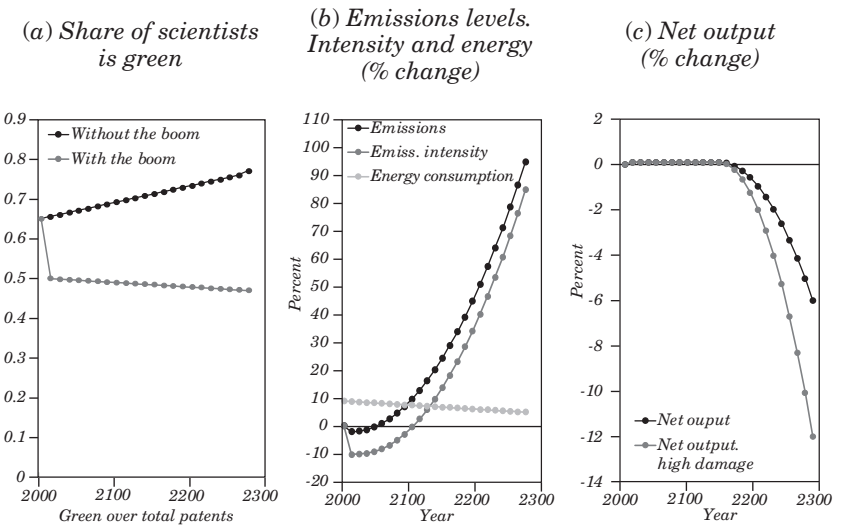
To analyze the long-run effect, we introduce endogenous directed innovation into the model by assuming that power plants can innovate using different sources of energy. Under the lens of the model, the shale gas boom directs innovation away from both coal and clean production technologies, into gas production technologies. This causes a problem in the long run because this process may switch the U.S. economy from a path with declining CO_2 emissions to a path with increasing CO_2 emissions. This could have happened with a fall in clean patents, as shown in Figure 10.

Figure 10. Clean vs. Dirty Patents in the U.S.



Source: Acemoglu and others (2023).

Figure 11. Long Run Consequences of Shale Gas Revolution



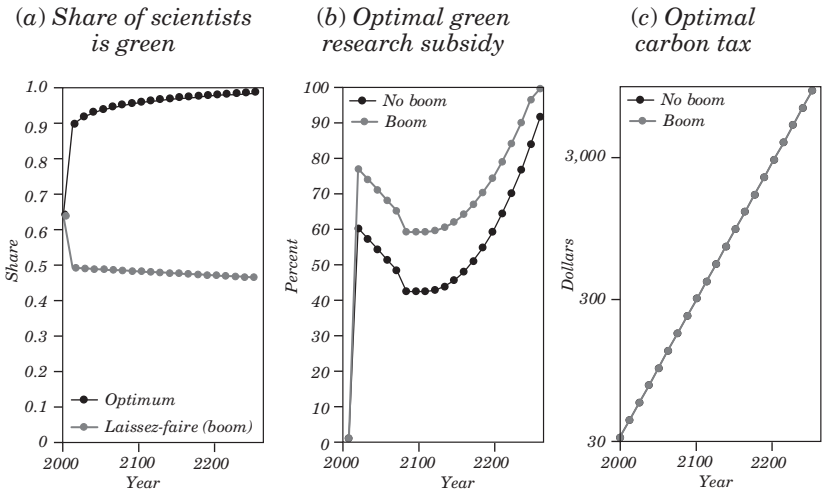
Source: Acemoglu and others (2023).

Or it could also be due to the scale effect, as shown in Figure 11. Panel A shows the path of a scientist working in green technologies with and without the shale boom happening, under the assumption that there is no government intervention. In the scenario where the shale boom occurs, we observe a discrete fall after the boom, followed by a decreasing tendency. The opposite happens in the scenario with

no shale gas boom. Panel B shows the difference in CO_2 emissions between the two scenarios. Initially, in the first 20 years, CO_2 emissions go down because the short-run effects dominate; but then, the emissions will grow at a fast pace, eventually surpassing the emissions in an economy without the boom because the long-run effects dominate. And because emissions will rise, panel C shows a sharp fall in the net output due to greater damages arising from global warming.

So, this long-run effect plays a very important role. In essence, the short-term gains were offset by long-term losses due to diverted innovation, causing the economy to move from a good trajectory towards a bad one. But if the government has the ability to act, then it raises the question of what the optimal policy could be, as there are gains from the boom in the short run. Figure 12 shows the optimal trajectory of the policies. Panel A shows that, to achieve the optimal trajectory, there is a need to compensate for the effects of the boom by adding more scientists researching green innovations as compared to the *laissez-faire* situation. Panel B shows that the subsidy of green research needed to achieve the optimal number of scientists doing green research is greater when the boom happens because we need to counteract the incentive of researchers to divert their efforts towards the shale gas technology. Regarding the optimal carbon tax, it does not change much between the two scenarios.

Figure 12. Policies' Optimal Trajectory



Source: Acemoglu and others (2023).

The main idea is that an intermediate energy source boom can be dangerous because it can redirect the innovations towards nonclean once, but it also can open an opportunity to have gains in the short run without losing the path of cleaner technologies if the right policies are applied.

2.3 The Role of Civil Society

So far, we have only discussed a role for the state. We argued a role for the state in directing firms' production and innovation. But what about civil society? Can the consumers help in any way? Aghion and others (2023) address this question. We first check if the consumers' valuation of the environment can shift the innovations of the firms towards clean technology.

Table 6. Regression Results

	(1)	*(2)*	*(3)*	*(4)*
Variables	*Log*(1+#*clean*)-*Log*(1+#*dirty*)			
Values	0.170***	0.229***	0.233***	0.594***
	(0.0397)	(0.0500)	(0.0524)	(0.144)
Competition	0.189***	0.161***	0.325**	-0.0223
	(0.0614)	(0.0605)	(0.139)	(0.0305)
Values x Competition	0.109***	0.0703***	0.0875***	0.0620**
	(0.0370)	(0.0234)	(0.0231)	(0.0243)
Log fuel price	0.766***	0.601**	0.151	0.856
	(0.235)	(0.244)	(0.236)	(0.663)
Competition measure	OECD	OECD	World Bank	Lerner
Values measure	Higher tax	Index	Higher tax	Higher tax
Observations	17,124	17,124	17,124	2,706
R-squared	0.121	0.122	0.121	0.199
Number of x bvdid	8,562	8,562	8,562	1,854

Source: Aghion and others (2023).

Going back to the automotive industry, looking at the propensity to innovate in green technologies, Table 6 shows the results of a similar regression but considering the countries where consumers value the environment. The variable value is constructed at the firm level as a weighted average of the valuation of each country where it has a presence and using the exposure of the firm to those countries as weights. All the specifications show that the consumers' valuation of the environment shape the firms' decisions on innovation.

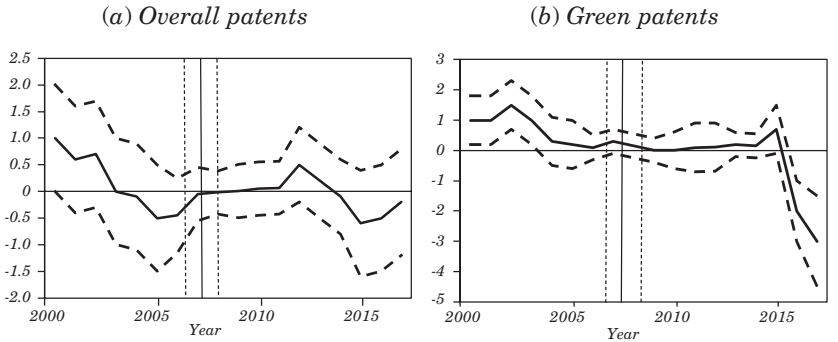
Now, let's talk about competition. Increasing competition could have two effects. The first one is a scale effect. The competition can reduce prices, thereby incentivizing consumption and boosting output, which ultimately increases emissions. But on the other hand, if consumers value the environment, more competition induces more green innovation, thereby reducing emissions. This happens because innovation is a tool used by firms to escape competition. Going back to Table 6, the third row captures this effect of the interaction of competition and value. Notice that the relation is positive in all specifications. This means that educating consumers and inducing more competition can have effects as important as a carbon tax.

3. Conclusion

There are three big conclusions for this paper. First, innovation-based climate-change models suggest that *laissez-faire* leads to disaster due to path dependence in the direction of innovation. Second, one must act now, and multiple instruments must be used, not just the carbon tax. Third, there is a direct link between firms, the state, and the civil society. Firms innovate, so they are necessary. But they do not spontaneously innovate in green technologies, so we need the state to redirect the innovation towards green technologies by imposing a carbon tax, green industrial policy, etcetera. Civil society also has a role to play. Consumers (and not only they but also the media and other forms of communication) can discipline firms.

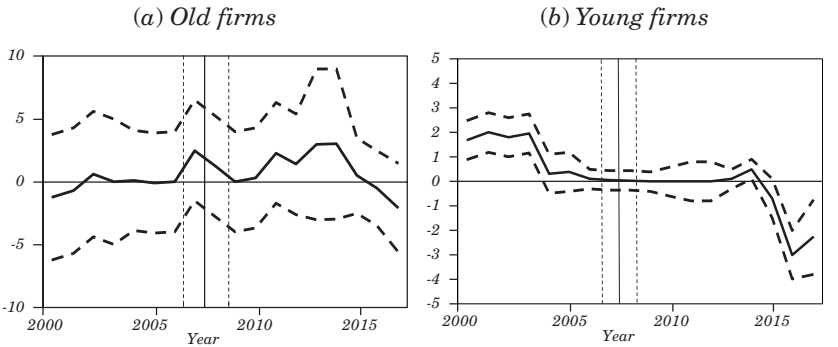
Digging into Green Industrial Policy, in Aghion and others (2024a), we consider the green energy transition along the value chain in the presence of Pigovian taxation. Complementarities across sectors can lead to multiple equilibria either where clean technologies are adopted along the value chain or where they are not adopted. This speaks to the role of industrial policy to coordinate the clean transition because with a Pigovian tax alone to remove multiplicity, one would need too large a tax.

Figure 13. Evolution of Patents



Source: Aghion and others (2024a).
Notes: The figure plots the effects of exposure to Commerzbank on patenting in the year on the horizontal axis. Estimates from PPML. Confidence bounds are at 95% level using firm-clustered standard errors.

Figure 14. Evolution of Firms



Source: Aghion and others (2024a).
Notes: The figure plots the effects of exposure to Commerzbank on patenting in the year on the horizontal axis. Estimates from PPML. Confidence bounds are at 95% level using firm-clustered standard errors.

Also, there is a role of finance. Finance is particularly helpful in understanding the financing of new firms. As we saw, endogenous directed innovation favors new firms because they do not have the burden of path dependence. That is, anything that will ease the entry of new firms could help with the process of green innovation, and the same is true when entry becomes costly. In Aghion and others (2024b), we look at the effect of exposure to German banking crises on green innovation. There is a fraction of firms that have links with Commerzbank. During the crisis, Commerzbank had to cut lending

after losses in its international trading portfolio. Figure 13 presents the results of a difference-in-difference approach.

For "overall patents", there is no difference in being a bank that suffered the crisis, but for "green patents", there is a slope. Figure 14 shows the patents by young and old firms. For old firms, the patents remained stable, unlike the new firms, which dropped. And we know that the new firms are the ones that do not have the path dependence cost, so they innovate more in green technologies.

Thus, the problem is that when we have a credit crunch, the firms that are harmed the most are the new ones, that is, the ones that are more prone to do green technology innovation. This stands out because it has implications for macro policy. From a monetary point of view, raising interest rates too much will slow down the transition to a low-carbon economy because it will make it difficult to finance small and new firms. From a budgetary standpoint, the management of public debt is relevant. Cutting subsidies for green technologies may save money, but this will imply that firms will continue to innovate in a dirty way because of path dependence, and it will be much more costly to make the transition later. So, in a sense, we will be leaving future generations with a huge environmental debt. Therefore, it is necessary to arbitrate between these two debts.

As a final point, it is important to recognize that there are different types of innovation. First, there is mitigation innovation, which aims to reduce the rise in temperature (such as the discovery of new energy sources). Next, we have adaptation innovation, like air conditioning, which helps us adapt to global warming. Finally, there are innovations focused on cooling, which seek to lower global temperatures. The question is—can we master this technology to achieve cooling? These types of innovations can be categorized into two broad categories. "Plan A" innovations, which aim to mitigate the effects of environmental degradation, and "Plan B" innovations, which are designed to help us survive in a warmer world. Some argue that focusing on Plan B innovations could undermine Plan A efforts. However, I disagree, because countries will not adopt Plan A or Plan B innovations simultaneously. Therefore, to effectively address the unique needs of each country, it is crucial to have all available tools at their disposal.

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Integrating Ecosystem Modeling into Economic Models: Applications to Efficiency Analysis, Gross Ecosystem Product, and Policy Analysis

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Unless you are one of the 676 people who have traveled to space as of November 2023,[1] you will have spent your entire life living within the biosphere, a relatively thin layer above and below the Earth's surface, where life exists. Spending our entire existence surrounded by the biosphere, it can be easy to take it for granted. But a livable biosphere is crucial for the health and well-being of humanity. One way to see the fundamental importance of the biosphere is to imagine living outside of it. In the science-fiction novel *The Martian*,[2] an astronaut finds himself alone on the surface of Mars and must figure out how to survive in an unforgiving environment, including meeting basic requirements like providing food and maintaining a breathable air supply. *The Martian* drives home a basic point: the Earth, unlike Mars or anywhere else in the universe as far as we know, provides humans with an essential life support system. When an article published in *Nature* estimated that the total annual value of the Earth's ecosystem services was $33 trillion,[3] economist Mike Toman wryly commented that it was a "serious underestimate of infinity."[4]

1. See Hobbs (2023).
2. See Weir (2014).
3. See Costanza and others (1997).
4. See Toman (1998).

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For most of human history, human actions did not appreciably change the biosphere except for some localized effects.

However, since the Industrial Revolution and particularly since the "Great Acceleration" in economic activity that began in the 1950s, humanity has had massive global impacts.[5] We now live in an era in which humans are the dominant force driving change in the biosphere.[6] Changes in the biosphere, including global climate change and loss of biodiversity, now threaten current and future prosperity and well-being.[7]

Maintaining a livable biosphere in which humanity can thrive will require large-scale changes in economic activity, including shifting energy production away from carbon-emitting fossil fuels and changes in agriculture, forestry, mining, development, industrial production, and other sectors that directly affect biodiversity. Harnessing economic incentives is essential for making changes in economic activity on the scale and at the speed necessary to address the climate and biodiversity crises. In 2005, the Millennium Ecosystem Assessment reported on global trends in biodiversity and ecosystems and focused attention on the concept of "ecosystem services," defined as goods and services provided by nature that benefit people. This assessment found that the provision of the vast majority of important ecosystem services had declined over the previous 50 years. The only exceptions to the general pattern of decline were the production of crops, livestock, and aquaculture, which are all private goods for which economic incentives for production are in place, along with net carbon sequestration.[8] This pattern of decline in the majority of the ecosystem services, except for the provision of material services that are private goods, was also found more recently in the Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).[9] Virtually all other ecosystem services are characterized by being provided by forms of natural capital that are public goods. Economic theory predicts the under-provision of public goods without some type of policy intervention. In reviewing the trends in ecosystem services, Kinzig and others (2011) noted "you get what you pay for" and, conversely, "you don't get what you don't pay for." These works highlight the urgent need to bring the values

5. See IPBES (2019); IPCC (2023).
6. See Crutzen and Stoermer (2000).
7. See IPBES (2019); IPCC (2023); UNEP (2021).
8. See MA (2005).
9. See Brauman and others (2020); IPBES (2019).

of nature into economic accounts and to provide economic incentives to preserve the natural capital that generates the flow of ecosystem services.

The primary motivation for developing integrated ecosystem-economic models is to bring information about ecosystem services and natural capital into economic and policy decision-making. Integrated ecosystem-economic modeling can be used to analyze the impacts of human actions on ecosystems, the resulting changes in the provision of ecosystem services, and the consequent impacts on the economy and human well-being. With this information, it is possible to assess the benefits and costs of various economic activities, including their effects on ecosystem services. By linking these impacts on ecosystem services to incentives—either through green subsidies (i.e., payments for ecosystem services), brown taxes (i.e., carbon and pollution taxes), cap-and-trade, or other policy mechanisms—the proper economic incentives can be given to businesses and households to maintain or enhance an efficient level of natural capital and provision of ecosystem services. Doing so would reorient economic activity towards maintaining a livable biosphere in which humanity can prosper well into the future.

The next section lays out the framework guiding the development of integrated ecosystem-economic models and their basic building blocks. The following section contains descriptions of various applications of integrated ecosystem-economic modeling. These applications include: i) local-regional scale benefit-cost analysis of policies or projects, ii) development of efficiency frontiers (production possibility frontiers) showing feasible combinations of outputs across multiple objectives, iii) private-sector disclosure of dependencies and impacts, iv) Gross Ecosystem Product (GEP), which aggregates the value of ecosystem services similar to GDP accounting of marketed goods and services, and v) global general equilibrium analysis that incorporates natural capital and ecosystem services.

1. An Integrated Ecosystem-Economy Modeling Framework

The purpose of integrated ecosystem-economic modeling is to bring ecosystem services and natural capital into economic and policy decision-making. One framework for bringing the value of nature into decision-making was laid out in Polasky and Segerson

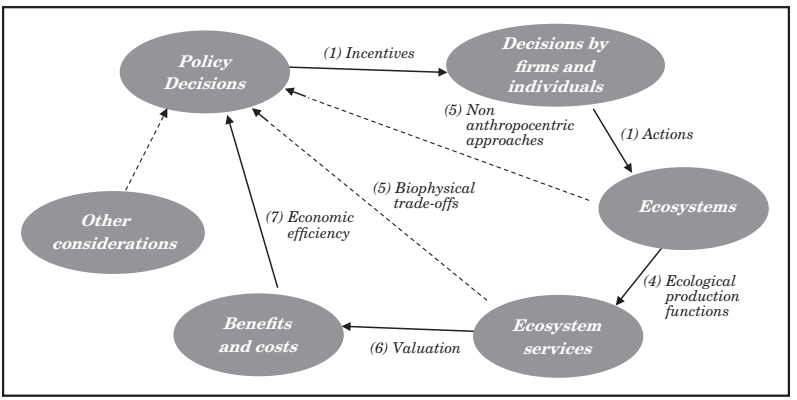
(2009), shown in Figure 1. Since the purpose of integrated ecosystem-economic modeling is to inform decision-making, the framework starts (and ends) with policy decisions, as depicted in the upper left oval in Figure 1. Policy decisions, such as whether to institute a carbon tax or payments for ecosystem services, affect incentives faced by businesses and households and can thus influence their decisions, as shown by arrow (1) in Figure 1. Businesses and households take actions that can impact ecosystems, for example, clearing land for crop production or grazing, harvesting biological resources (hunting, fishing, and gathering), changing nutrient flows through fertilizer application, changing hydrological cycles from irrigation and other water uses, and emitting air or water pollutants and greenhouse gases, as shown by arrow (2) in Figure 1. A branch of the environmental sciences analyzes impacts on nature from various economic activities, such as the impact of habitat loss on biodiversity or the greenhouse gas emissions on climate change and their subsequent impacts on ecosystems. Environmental science often stops at this point, showing how actions impact the environment in biophysical terms. Sometimes this is sufficient for policy decisions, as for example, demonstrating that an action causes harm to an endangered species listed under the U.S. Endangered Species Act or that pollution emissions into a waterbody violates water quality standards under the U.S. Clean Water Act. A major disadvantage of this approach, however, is that it doesn't determine whether a regulatory prohibition will result in an increase or decrease in social net benefits because there is no calculation of benefits or costs. There may also be impacts on other sectors or geographic regions, such as when strict regulations in one country cause a shift in production to other countries with less strict regulations, which also typically do not get factored into the analysis.

Impacts on ecosystems may or may not cause impacts on human well-being. For an ecosystem function to be considered an ecosystem service, it must generate a benefit to some person. If eliminating the function does not affect the well-being of any person, whether present or future, then the ecological function is not an ecosystem service. Going beyond ecological functions and biophysical impacts, ecosystem service modeling uses "ecological production functions" to determine the provision of ecosystem services as a function of the condition of ecosystems, as shown by arrow (4) in Figure 1. For example, the extent and condition of vegetation within ecosystems affect the degree to which the ecosystem can filter pollutants, regulate pests and pathogens, modulate floods or droughts, provide habitat for

charismatic species, or provide other valuable benefits that people care about. Ecological production functions for multiple ecosystem services can be used to identify tradeoffs among ecosystem services such as between expanded food production and maintaining water quality and carbon sequestration, as shown by arrow (5) in Figure 1.

Ecological production functions defining the provision of ecosystem services can be combined with economic valuation to determine the value of the contribution of ecosystem services to human well-being, as shown by arrow (6) in Figure 1. The value of the provision of ecosystem services can be estimated in monetary terms by using market and nonmarket valuation methods. The great advantage of using economic valuation is that it puts the contribution of all ecosystem services into a common (monetary) metric, making it easier for decision-makers to determine which policy alternatives or management choices deliver the highest net benefits, as shown by arrow (7) in Figure 1.

Figure 1. Framework for Integrated Ecosystem-Economy Modeling Connected to Decision-Making



Source: Polasky and Segerson (2009).

Currently, the monetary valuation of all ecosystem services is difficult to achieve in practice. Because many ecosystem services are not traded in markets and therefore do not have market prices, nonmarket valuation methods must be used to assess value. Nonmarket valuation methods work quite well for some ecosystem services, such as assessing the value of recreation by using random utility travel cost methods or the value of natural amenities on property value by using hedonic property price methods.[10] Other ecosystem services are inputs into marketed goods and services, and their value can be imputed by using the marginal value product along with the market price of the marketed good or service. For example, the value of pollination can be imputed by estimating how pollination contributes to the quantity and quality of agricultural crop production and the consequent increase in crop revenue.[11] Some ecosystem services, though, are difficult to measure in monetary terms, especially nonmaterial ecosystem services such as those that contribute to cultural or spiritual values, sense of place, or experience.[12] It is also difficult to get an accurate estimate of the present value of the flow of future ecosystem services caused by changes in natural capital. Besides the normal difficulties of knowing how to discount future values, there is also the difficult task of predicting how much of each ecosystem service will be provided in the future and the value of those services to future generations.

In part because of the difficulty of getting fully accurate estimates of the value of all ecosystem services, comparing the net benefits of policy or management alternatives using ecosystem service valuation should be viewed as an important input into decision-making, but not determinative of the decision itself.[13] Additional factors such as distribution or equity concerns or information about values that are difficult to quantify or monetize may also be important to consider in decision-making (Figure 1).

Many components of the integrated ecosystem-economic framework described above are well-developed in the natural sciences and economics. Ecosystem ecology studies ecosystem functions and many environmental sciences study how the environment is impacted by various human actions. Environmental economics has developed methods of market and nonmarket valuation that can be applied

10. See Freeman and others (2014).
11. See Ricketts and others (2004); Ricketts and Lonsdorf (2013).
12. See Daniel and others (2012); IPBES (2019).
13. See Arrow and others (1996).

to value ecosystem services. Economists have also studied a wide variety of policies and incentive mechanisms and how these influence decisions, including decisions that have an impact on the environment.

While these components are often available, what is more often missing is the integration of these parts into a complete analysis—one that connects a policy or management change to its impacts on ecosystems, to subsequent changes in ecosystem services, and ultimately, to changes in human well-being. The parts of this integration that have drawn the least attention typically occur at the junctures linking natural sciences and economics. Natural scientists are comfortable doing natural science, and economists are comfortable doing economics. It takes a concerted effort to overcome disciplinary silos to combine natural science and economic analysis into a single integrated analysis. The first of these key junctures between natural science and economics comes from connecting the way in which policies and incentives translate to actions, which is largely in the realm of economic analysis, to their effects on ecosystems and environmental impacts. Most of the information to establish this connection exists but often work is needed to translate economic decisions into changes in ecosystems that can then be used in ecological production functions. Changes in land use or emissions of greenhouse gases have received the most attention and are furthest along in this regard. At a more micro level, how agricultural practices and management affect ecosystems is well studied, as are the impacts of many particular industrial practices. The second key juncture between natural science and economics comes from the need to link changes in ecosystem structure and function to the provision of ecosystem services that benefit people, and ultimately to their value to people. Ecological production functions are well understood for some ecosystem services, such as carbon sequestration and storage, or the contribution to material goods, such as agricultural crops, timber, and fisheries. For many other ecosystem services, such as the physical and mental health benefits of exposure to nature, the production functions are still works in progress.

Even with imperfect knowledge of some ecosystem service values, analysis incorporating what is currently known about ecosystem services can provide useful information to inform decisions. The next section presents example applications that illustrate this point.

2. Applications Of Integrated Ecosystem-Economy Modeling

Information about the value of ecosystem services can be used in a variety of contexts to inform public- and private-sector decisions. This section describes five types of applications of integrated ecosystem-economy modeling and provides illustrative examples, starting with local- to regional-scale benefit-cost applications of policy or project alternatives and ending with global-scale general equilibrium models.

2.1 Local-Regional Scale Benefit-Cost Analysis

Benefit-cost analysis is a useful tool for helping to inform policy and management decisions, but the results are only as good as the inputs used. Leaving out major categories of benefits or costs can result in biased information and poor decisions. Including information about ecosystem services and the impacts of alternative policy or management decisions on ecosystem services can improve benefit-cost analysis and the information it provides for decision-making. Over the past two decades, The Natural Capital Project—a partnership between Stanford University, the University of Minnesota, the Chinese Academy of Sciences, the Royal Swedish Academy of Sciences, the Stockholm Resilience Center, The Nature Conservancy, and the World Wildlife Fund—has developed the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software package, which is a suite of ecosystem service models using biophysical, land use, and land management inputs, to predict provision of a set of ecosystem services.[14] At its core, InVEST is a set of ecological production functions that take biophysical inputs characterizing the extent and condition of ecosystems and generate outputs describing the provision of ecosystem services. The InVEST software has been downloaded thousands of times and has been used in countries around the world.

Polasky and others (2011a) used an early application of the InVEST software to analyze the benefits and costs of alternative land-use policies on several important ecosystem services. Using data from the state of Minnesota, they parameterized InVEST, and several other models to analyze the impact of alternative land-use plans covering the period from 1992 to 2001 on carbon sequestration, water quality

14. See website of The Natural Capital Project, Standford University.

(phosphorus contributions to rivers and streams), habitat quality for grassland and forest birds and general terrestrial biodiversity, agricultural crop and timber production, and the value of land use in urban development. The authors found that incorporating the values of several ecosystem services (carbon sequestration and water quality) changed the ranking of net benefits among alternative land-use policies compared to the case without incorporating ecosystem service values. When just considering the private returns to landowners, the agricultural expansion scenario, in which all highly productive land for agriculture was put into crop production, generated the highest net market returns among the scenarios (bottom row in Table 1). The agricultural expansion scenario, however, generated the lowest net social benefits across all scenarios considered when ecosystem services were included because of the large losses in stored carbon and negative impacts on water quality in this scenario (top row in Table 1). Further, this scenario resulted in the largest decline in habitat quality for general terrestrial biodiversity and forest songbirds. Values associated with biodiversity conservation were not monetized and not included in Table 1. Inclusion of biodiversity values would only worsen the relative outcomes for the agricultural expansion scenario. In contrast, the no agricultural expansion scenario with no new cropland generated the highest net social returns when the value of carbon sequestration and water quality were included. This alternative and the conservation scenario, in which lands within 100 meters of streams and agricultural lands with marginal soils were restored to natural vegetative, were the only two scenarios with a positive net social benefit relative to the no change in land use scenario (column 2 in Table 1).

The results in Polasky and others (2011a) show the importance of including the benefits and costs associated with changes in ecosystem services for policy decisions. The finding that the inclusion of ecosystem service values changes the ranking among policy alternatives is consistent with other studies, including comparing the social net benefits of maintaining natural habitat versus land conversion,[15] alternative land uses in the Willamette Basin, Oregon, USA,[16] and alternative policies affecting land use for the U.S.[17]

15. See Balmford and others (2002).
16. See Nelson and others (2009).
17. See Lawler and others (2014).

Table 1. Value of Ecosystem Services and Private Returns to Land under Land-Use Change Alternatives

	Actual land use in 1992	*No agriculture expansion*	*No urban expansion*	*Agriculture expansion*	*Forest expansion*	*Conservation*
Change in total value: carbon, water quality, agriculture & forest production, and urban development using actual prices (million 1992 US dollars)	$3,328	$3,407	$3,040	$2,742	$3,300	$3,380
Change in returns to landowners: agriculture & forest production, and urban development using actual prices (million 1992 US dollars)	$3,320	$3,343	$3,027	$3,418	$3,292	$3,221

Source: Polasky and others (2011a).

2.2 Efficiency Frontiers

Even when information about the value of some ecosystem services is unavailable, information about the quantity of ecosystem services can still be useful for decision-making. Ecological production functions define the quantity of ecosystem services that can be produced with available inputs. Using optimization techniques along with ecological production functions, an efficiency frontier (production possibility frontier) can be derived showing Pareto-efficient combinations of ecosystem services that can be achieved with a given set of resource

inputs.[18] The efficiency frontier shows the biophysical tradeoffs between services; i.e., the slope of the efficiency frontier is the marginal rate of transformation between ecosystem services. The efficiency frontier can also show the degree of inefficiency of various alternative resource allocation plans including the current allocation and what changes can be made in allocations that would lead to Pareto improvements.

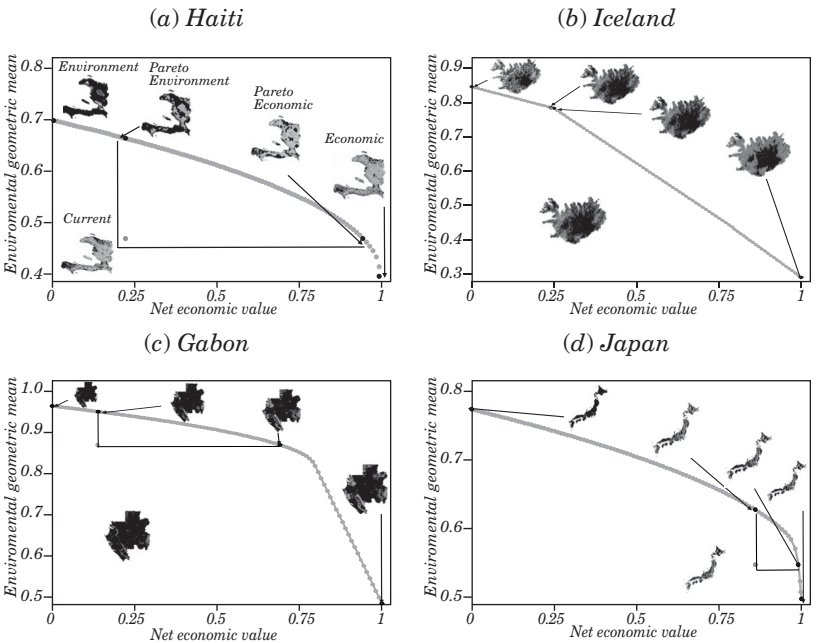
In recent work involving colleagues from the Natural Capital Project and the World Bank, landscape efficiency frontiers showing Pareto-efficient land-use patterns were derived for 146 countries.[19] For each country, the landscape efficiency frontier shows how land should be allocated to different uses, which in this analysis included crop production, livestock grazing, timber production, and conservation as natural habitat, in order to generate Pareto-efficient combinations of multiple ecosystem services, which in this analysis included carbon storage in terrestrial ecosystems, biodiversity conservation, and the value of net returns to crop production, livestock grazing, and timber production. The analysis showed that the current land-use pattern in many countries was far from the efficiency frontiers, indicating that large environmental and economic gains were possible, even when factoring in transition costs for switching land use. For example, in Haiti, it is possible to improve carbon storage, biodiversity, and the net value of agricultural crops, livestock, and timber production, relative to the current landscape by large percentages (panel A in Figure 2). Not all countries can simultaneously improve outcomes in multiple dimensions, such as Iceland (panel B in Figure 2). Many sparsely populated low-income countries, such as Gabon, can greatly increase the value of market returns while maintaining high levels of biodiversity and carbon storage (panel C in Figure 2). Many highly developed and densely populated countries, like Japan, can improve biodiversity and carbon storage without loss of market value. However, restoring environmental outcomes to anything close to what they once were would require large sacrifices in the value of market returns (panel D in Figure 2). Across all 146 countries, improved land use and land management can increase carbon storage by 233 billion metric tons of CO_2 (23 percent increase from current levels) while also increasing biodiversity without loss of net production value from crops, grazing, and timber, or increase the net value of production by

18. See Polasky and others (2008).
19. See Damania and others (2023); Polasky and others (2023a).

367.7 billion U.S. dollars (83 percent increase) without loss of climate mitigation or biodiversity benefits.[20]

An advantage of efficiency frontiers is that they highlight potential efficiency gains, the actions that can be taken to realize efficiency gains, and the unavoidable tradeoffs between various ecosystem services and between ecosystem services and other goods and services. Efficiency frontiers also do not rely on prices or values, which can be difficult to obtain for some (nonmarket) ecosystem services. The disadvantage of efficiency frontiers is that there is no obvious best outcome. Rather, decision-makers need to contribute their own value judgments to decide which Pareto-efficient outcome is viewed as best.

Figure 2. Landscape Efficiency Frontiers and Current Performance



Source: Polasky and others (2023a).

Notes: The figure shows potential simultaneous gains for environmental and economic outcomes and tradeoffs for illustrative countries. The horizontal axis measures the net production value from agricultural crop production, livestock grazing, and forestry. The vertical axis is the geometric mean of carbon storage and biodiversity scores. Minimum and maximum scores in each country for each outcome are normalized to 0 and 1 with maximum environmental geometric scores often occurring at negative production values because of transition costs from the current landscape that outweigh positive production value at the landscape that maximizes environmental outcomes.

20. See Polasky and others (2023a).

2.3 Private-Sector Disclosure of Dependencies and Impacts

While most ecosystem services evaluations to date have been focused on public-sector decision-making, a similar analysis can be done to inform private-sector decision-making. The major difference between the ecosystem information relevant to private-sector and public-sector decision-making is the scope of the accounting. For a business, the appropriate scope for accounting can include the direct impact of the business's operations on the provision of ecosystem services (Scope 1) or the impact of the business through its entire supply chain—from purchased inputs through to impact from consumer use and the end of the life of the product (scopes 2 and 3). Like public-sector applications, business applications measuring impacts can be done in both biophysical and monetary terms and, like public-sector applications, measurement in a common monetary metric facilitates comparisons of the profitability and/or social net benefits of alternative business strategies. Measures of impact are also of interest to financial analysts evaluating businesses or investment portfolios.

To measure the impacts of a business on ecosystem services, information is needed on the location of company operations ("where"), the production processes at each location ("what"; i.e., what products are produced and by what processes), and the scale of activities at each location ("how much").[21] This type of information is often proprietary. However, using publicly available information on the location and size of business operations, along with life-cycle analyses by industry, dependencies and impacts can be estimated even without access to proprietary information.

Currently, there is great interest in the disclosure of business impacts on nature, spurred by impending mandatory disclosure rules in the European Union under its Corporate Sustainability Reporting Directive (CSRD). In addition, there are voluntary disclosure rules published by the Taskforce on Nature-Related Financial Disclosure (TNFD), similar in spirit to carbon disclosure rules published by the Task Force on Climate-Related Financial Disclosure (TCFD), and the Methodological Assessment of the Impact and Dependence of Business on Biodiversity and Nature's Contributions to People by IPBES.

21. See Polasky and others (2023b).

2.4 Gross Ecosystem Product (GEP)

The development of Gross Domestic Product (GDP) within an agreed-upon standardized System of National Accounts provided government leaders with a clear macroeconomic measure of economic performance. There is currently no similar agreed-upon and widely quoted number for environmental performance and its contribution to human well-being. However, when market prices for ecosystem services or calculable shadow prices for nonmarket ecosystem services are available, it is possible to aggregate the value of all ecosystem services into a measure of "Gross Ecosystem Product" (GEP) in a manner similar to the aggregation of the value of final goods and services measured by GDP. Accordingly, GEP is defined as the aggregate monetary value of ecosystem services in a given region (city, county, province, country) in a given accounting period, typically a year.[22] GEP is calculated using methods that parallel the methods used to calculate GDP. Just as GDP summarizes the complex operations of an entire economy in a single monetary metric that is readily understood by decision-makers, GEP summarizes the aggregate value of nature's contributions to the economy in a single easily understood number. There is overlap between GDP and GEP because both measure the value of marketed ecosystem services, so GDP and GEP cannot simply be summed together to derive anything meaningful, as shown in Figure 3. GEP is meant to complement, not replace, GDP by providing different but related information.

Although calculating GEP is challenging for the reasons discussed above regarding the difficulties of understanding ecological production functions as well as of using nonmarket valuation, it is possible to calculate GEP with existing data for a set of important ecosystem services. Ouyang and others (2020) calculated GEP for Qinghai province in China using data from the China Ecosystem Assessment for the years 2000 and 2015. Qinghai is known as the "water tower of Asia" because it contains the source of the Mekong, Yangtze, and Yellow rivers. The authors found that water-related ecosystem services made up nearly two-thirds of the value of GEP. Water runoff from Qinghai contributes to hydropower generation, agricultural irrigation, and industrial and household consumption. They also found that GEP more than doubled from 2000 to 2015. Part of this increase in value was due to large-scale investment in ecosystem restoration that increased the

22. See Ouyang and others (2020).

supply of some ecosystem services. The larger part of the increase in value was due to increases in the per-unit value of ecosystem services arising from a greater demand for ecosystem services through time, such as the greater value of downstream water use from increased population and economic activity.

Figure 3. The Relationship between GDP and GEP

Source: Zheng and others (2023).

The government of China has supported the development and use of GEP by county, city, and provincial governments and has adopted a common set of guidelines for calculating and reporting GEP. The goal in China is to have all levels of government report GEP alongside GDP on a regular basis. GEP can be used to reveal the contribution of ecosystems to the economy and human well-being, to show the ecological connections among regions, to be the basis for compensation from beneficiaries to suppliers of ecosystem services, and to serve as a performance metric for government officials.[23] GEP is also being used to support "Two-Mountains Banks," which provide favorable loans to enterprises that invest in activities that promote ecosystem services.[24]

2.5 Macroeconomic Analysis: GTAP-InVEST

At a macroeconomic scale, ecosystem service information can be integrated with computable general equilibrium models to show how economic activity drives changes in ecosystems, changes in the provision of ecosystem services, and in turn, how changes in ecosystem services affect the economy, including impacts on economic production and employment in various sectors, trade, and GDP. This integrated "earth-economy" model can be used to analyze likely trajectories for ecosystems and the economy under business-as-usual policies and can also show the economic consequences of gains or losses in ecosystem services. The integrated model can also be used to analyze the effects of policies, such as carbon taxes or payments for ecosystem services, on ecosystem services and economic performance.

Johnson and others (2023) integrate a computable general equilibrium model of the economy from the Global Trade Analysis Project (GTAP) with the InVEST model of ecosystem services. The resulting integrated earth-economy model jointly determines land use, environmental conditions, ecosystem services, market prices, supply and demand across economic sectors, trade across regions, and aggregate performance metrics like GDP. In an initial application of the earth-economy model, the authors included four ecosystem services: crop pollination, timber provision, marine fisheries, and carbon sequestration, and showed that under a business-as-usual scenario, economic activity would cause a decline in these four ecosystem services leading to a reduction in annual GDP of $75 billion. They also

23. See Ouyang and others (2020).
24. See Zheng and others (2023).

analyzed outcomes under five policy options: removing agricultural subsidies and giving lump-sum payments to landowners, removing agricultural subsidies to fund increased investment in agricultural research and development, instituting Payments for Ecosystem Services (PES) financed by international transfers from high-income to low-income countries, instituting a national-level PES where each country funds its own PES program, and a combination policy that removes agricultural subsidies to fund increased investment in agricultural research and development along with an international transfer PES program. Johnson and others (2023) find that these policies increased GDP by $100 to $200 billion annually relative to the business-as-usual scenario. As noted above, however, GDP fails to capture the full value of ecosystem services by failing to capture the value of nonmarket ecosystem services. Adding in the benefits of additional carbon sequestration by using a social cost of carbon of $185 per ton of carbon[25] raises the value of annual benefits for the combination policy to almost $350 billion annually.

Work on global-scale earth-economy models is only just beginning. Global-scale modeling of ecosystem services using globally consistent data and methods has only started to be done recently,[26] and links between ecosystem service models and computable general equilibrium models are also fairly recent.[27] Only a small number of ecosystem services have been included to date. Even so, this work already makes a compelling "economic case for nature,"[28] which will likely become more so with the addition of more complete models including more services, and as natural capital becomes scarcer.

3. Discussion

Economic activity is causing rapid changes in the biosphere. Accurate accounting of the provision of ecosystem services and their value, along with policy mechanisms to provide economic incentives to maintain the natural capital that supplies valuable ecosystem services, is needed to halt, and reverse, the deterioration of natural capital. Providing accurate information on the value of natural capital and ecosystem services that leads to improved policy and management

25. See Rennert and others (2022).
26. See Chaplin-Kramer and others (2019, 2023).
27. See Banerjee and others (2019, 2020); Johnson and others (2020, 2021).
28. See Johnson and others (2021).

decisions can in turn lead to large improvements in human well-being and biodiversity over the long run.

The agenda of accurate accounting tied to economic incentives has already gained traction in the climate policy community. Over the past several decades, much effort has gone into getting ever more refined carbon accounting along with efforts to better understand the social cost of carbon, which at least in theory, measures the present value of damages from emitting one ton of carbon to the atmosphere. As of the end of 2023, fifty-two national governments and 42 subnational (state and local) governments have adopted some form of carbon pricing—whether a carbon tax, emission-trading system, or government credit mechanism—,[29] and there is abundant literature containing estimates of the social cost of carbon.[30] Though coverage of climate policies is far from complete and many of these policies have prices well below current estimates of the social cost of carbon, the principles of what an efficient climate policy should look like have been laid out, and important steps towards efficient climate policy have been taken.

Ecosystem service accounting is, unfortunately, far more complex than climate accounting and valuation. While there is a single carbon budget, there are numerous ecosystem services. For virtually all ecosystem services, the location of where things occur matters much more than for greenhouse gas emissions because greenhouse gases globally mix in the atmosphere. Despite these difficulties, as shown in the applications in the previous section, many of the parts of what is needed to accurately account for ecosystem services and the knowledge of how to create economic incentives for continued provision of ecosystem services already exist. Understanding the ecological production functions is well advanced for many of the most important and valuable ecosystem services, as is understanding the market and nonmarket value of many important ecosystem services.

There is, of course, no shortage of ways in which accurate accounting and policymaking for ecosystem services could be, and should be, improved. Incorporating ecosystem services into economic and policy decision-making is still in its infancy, and many frontiers of analysis remain to be more fully developed. Further improvements are needed for ecological production functions as well as for market and nonmarket valuation, particularly for the many ecosystem services

29. See World Bank (2023).

30. See, for example, Barrage and Nordhaus (2024); Rennert and others (2022); Rode and others (2021).

that have not received as much attention to date. Some impacts of economic activity on ecosystems and ecosystem services that have not received much attention may turn out to be quite important. For example, the costs associated with air pollution from land use and land management (particularly agriculture) tend to be large, often larger than the direct monetary benefits from the economic activity.[31] The present value of the global social cost of eutrophication-driven methane emissions from lakes between 2015 and 2050 was estimated to be between $7.5 and $80 trillion.[32] There are probably other important ecosystem services still waiting to be quantified and valued.

Other areas where improvements are needed are the handling of uncertainties, of which there are many, and issues involving dynamics. Many ecosystem service analyses, including several discussed in this paper, report point estimates. While these may be the best guesses of value, they are likely to have significant errors because of both biophysical and economic uncertainties. One area for improvement involves better reporting and communicating important uncertainties to decision-makers, as well as improving decision-making under uncertainty.[33] Climate change, soil degradation, population declines, and species extinctions are all examples where state variables in biophysical systems change through time, potentially causing large changes in ecosystem service provision. Changes in manufactured capital, human capital, and institutions can similarly have large impacts on future values of ecosystem services. Developing integrated models with dynamic feedback effects between ecosystems and economic systems is another high priority for modeling improvements. Combining uncertainty with feedback effects can be particularly daunting, as ecological-economic systems may undergo regime shifts involving rapid fundamental shifts from small changes in initial conditions.[34] Finding methods of early warnings for potential catastrophic regime shifts[35] and taking the potential for regime shift into account in management[36] are two strategies for addressing this challenge.

Improving integrated ecosystem-economy models and generating reliable information for public- and private-sector decision-makers is

31. See Goodkind and others (2023).
32. See Downing and others (2021).
33. See Polasky and others (2011b).
34. See Scheffer and others (2001).
35. See Biggs, Carpenter, and Brock (2009); Carpenter and others (2011).
36. See Polasky and others (2011c).

a vitally important task for addressing the rapid decline of natural capital and ecosystem services. These models are improving and can be applied to a variety of contexts from micro- to macroeconomic scales. Economists have a central role to play in developing integrated ecosystem-economy models, just as economists played a central role in developing integrated assessment models to provide policy-relevant information on climate change. Even though integrated ecosystem-economy models are currently far from perfect, the pressing need to reverse the decline in natural capital and ecosystem services means there is no time to waste. The best way to improve rapidly on many fronts is to get started without waiting for perfection.

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Introducing Natural Capital in Macroeconomic Modeling*

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Biodiversity loss is now widely perceived as a potential source of significant economic and financial instabilities.[1] This is intuitive since biodiversity loss is not only a risk for the environment and a direct threat to nonhuman species but also a menace to human civilization, which relies on Nature to produce goods and services essential to its livelihood. More impactfully, *"ecosystem services"* are what makes human life possible. Among the most obvious services are food, water, plant materials that generate fuel, infrastructure materials, and drugs. Less visible but certainly not less essential, ecosystem services include climate regulation and natural defenses from natural forces provided by forests, carbon sequestration, or the pollination of crops by insects. Less directly apparent services also include culture, inspiration, and the sense of purpose that living in a healthy and thriving natural world gives humans every day.

Problematically, the major drivers of biodiversity loss are "byproducts" of economic material growth and production[2] This conundrum might seem particularly acute in developing economies, where the Environmental Kuznet Curve (EKC) paradigm has taken

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1. See NGFS (2023).

2. See IPES (2016).

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a hold, suggesting that there is an inescapable road that links economic development to environmental degradation (in this case via pollution). Despite the popularity in the economic profession and public discourse, there is however very weak (if at all) sound statistical work pointing out that such relationship in fact exists.[3] Recognizing that EKCs might be an artifact resulting from bad econometrics is undoubtedly encouraging, as it points to an absence of determinism in the way societies can develop materially while, at the same time, avoiding unsustainable deterioration of the natural environment.

If it is indeed realistic to think about paradigms that allow for sustainable development, one question is then why the economic profession (macroeconomists in particular) has been so quiet on the issue. In fact, while the study of how we should be addressing climate change has been at the forefront of debates and analysis since the early 1990s,[4] the notion of biophysical limits to growth has not yet taken root in modern macroeconomics.[5] As a result, prevalent macroeconomic theory still assumes that economic agents have access to boundless natural resources and bottomless sinks for waste products, thereby eliminating the need for an explicit discussion of economic growth within a natural world.

In this paper, we will first discuss how economic models have been slowly expanded to account for natural resources, and then present an analytical section describing how to set up a "bio-economic" dynamic stochastic general equilibrium (DSGE) model, also showing some simulation results. This latter section primarily builds on the work of Batini and Durand (2024), where biodiversity (equivalently referred to as "Natural capital" or "Nature" *tout court*) is defined as "the world's stocks of natural assets, which include geology, soil, air, water, and all living things" (following the definition of the *Convention on Biological Diversity*). In a final section, we will then summarize three macro-themes that could guide further modeling extensions, with an eye on topics that are relevant for macroeconomists working at central banks and other policy institutions.

3. See Stern (2017).

4. See Nordhaus (1991).

5. While economic activities that produce CO_2 tend to also directly affect the environment, the overlap is partial—for example, mineral extraction does not generate significant CO_2 emissions and yet it is responsible for significant ecosystem services degradation; the same goes for agricultural monocoltures.

1. Macroeconomics of Nature

Modern growth models, like the Solow-Swan neoclassical growth model,[6] do not consider the natural foundation of production. Accordingly, capital goods and labor are combined to produce commodity output, but no land is required as a site, no materials are needed from which to form commodities, and no energy is required to drive the process of commodity production and exchange. As Solow himself remarked, *"The production function is homogeneous of first degree. This amounts to assuming that there is no scarce nonaugmentable resource like land."*

In the 1970s, in response to emerging resource constraints from global energy price shocks and rising pollution, attempts were made to integrate natural resources (as distinct from natural capital) among factors of production and growth in economic models. Initial efforts focused on augmenting traditional input factors with a "nonrenewable resource" factor devising prescriptions for the exploitation of natural resources compatible with constant per capita consumption into the indefinite future.[7] This literature built on the insights from Hotelling (1931), who first showed that, in a competitive market assuming constant marginal extraction costs, extraction of the exhaustible resource should be such that the increase in price minus marginal costs equals the rate of discount (while marginal revenue minus marginal costs should rise at the rate of discount in the case of a monopolistic market).

In the 1980s, mounting environmental pressures and rising temperatures, coupled with expanding federal budget deficits in the United States, contributed to the emergence of a literature centered on the use of environmental levies to address fiscal deficits and on the possible use of environmental regulation to generate revenues that could in turn be used to compensate for other pre-existing distortionary taxes (such as on capital and/or labor). Pearce (1991) might be the first one to refer to the term "double-dividend" to express the idea of using carbon levies to finance reductions in other incentive-distorting taxes. The hypothesis was at the center of a rich debate, with works such as Bovenberg and De Mooij (1994) and Bovenberg and Goulder (1996) arguing that environmental taxes exacerbate rather than alleviate

6. See Solow (1956).

7. See Solow (1974), Stiglitz (1974), Dasgupta and Heal (1974), Dasgupta and others (1978), and Hartwick (1977).

pre-existing tax distortions. Overall, as lucidly pointed out by Fullerton and Metcalf (1997), the validity of the hypothesis cannot be settled as a general matter, as it depends on specific circumstances ultimately requiring case-by-case assessments.

Further attempts gradually expanded the concept of "natural resources" in economic models, moving towards notions better aligned with ecological economics definitions of natural capital. This stream of research included efforts to embed limits to sustained growth from increased pollution (seen as a phenomenon degrading the natural environment) through pollution-reducing technological change.[8] While most of these works concern pollution flows and abatement technologies, some begin to embed natural processes that can regenerate through time—"environmental quality" in the words of Acemoglu and others (2012). In these latter cases, there is a significant departure from previous work on nonrenewable resources, and the Hotelling condition is now expanded to also account for the intrinsic growth rates of the resource stock and the size of the stock relative to its long maximum size. Both concepts are at the core of the management of natural capital.

Along this line of work, Brander and Taylor (1997) analyzed the dynamic system of population interactions with natural resources, finding that an excessive rate of exploitation of stocks of resources tends to generate cycles in both population and natural capital. Dalton and others (2005) extended the model to technological change dependent on institutional parameters showing, for example, that institutions that favor strong property rights tend to bias technological change toward resource conservation rather than encourage or enable resource depletion.

Others have tried to model natural capital as a renewable resource[9] examining how to link material production and consumption to the pace of anthropogenic degradation of natural capital or, in some other cases, studying the impact on trade[10] and the inter-generational aspects of its exploitation[11] and, more recently, also emphasizing

8. See, for example, Tahvonen and Kuuluvainen (1991), Bovenberg and Smulders (1995), Howitt and Aghion (1998), and more recently, Brock and Taylor (2010), Acemoglu and others (2012), and Hassler and others (2016).

9. See Costanza and Daly (1992), Hinterberger and others (1997), Bringezu and others (2003), Comolli (2006), Fischer-Kowalski and others (2011).

10. See Karp and others (2001), also following environmental reforms by Karp and others (2003).

11. See Mourmouras (1991).

political economy aspects.[12,13] This literature stands in contrast with mainstream approaches, which are usually focused on the role of natural resources, and instead emphasizes the creation of ecosystem services. These works generally share the assumption that there can only be limited substitutability between natural capital and other forms of capital, which in turn implies a form of strong sustainability[14] meaning, at a minimum, that over the long run the economy must converge to a state where the total stock of natural capital remains constant over time. This is different from what is referred to as "weak sustainability" (or also "Solow sustainability",[15] which posits constant consumption per capita through time. Also, these models are distinctive in that they start to embed the possibility that there is some boundary usage of nature which, when crossed, provokes large changes in ecosystems behavior. This latter characterization is well aligned with the latest findings in ecological sciences showing both the presence and the possible self-reinforcing effects between separate tipping points, such as those from an Amazon dieback, Arctic sheet meltdown, and collapse of the ocean circulation pattern.

With a growing recognition of the urgency of accounting for ecosystem services degradation and their impact on human welfare came new studies, including Albagli and Vial (2023), who tried to disentangle the role of economic growth and population in driving biodiversity losses, proposing alternative growth pathways that would ensure conservation. One conclusion is that population growth dominates the negative impact of economic growth on biodiversity. This research follows the ecological economics footsteps pointing to limits to growth, for example by Schumacher (2011). Meadows and others (1972), Meadows and others (2004), and Costanza and Daly (1992) suggest that it is necessary to dematerialize growth to decouple production from resource use to ensure that the use and consumption of natural capital remains sustainable.

A difficulty behind these prescriptions is that both empirical evidence and theoretical work suggest that decoupling economic growth from the growth of material and energy use is unprecedented on the scale and time needed to stabilize the Earth system and might

12. See Karp and Rezai (2014).

13. Subsequent interpretations tried to define natural capital more comprehensively equating it to the sum of the stock of renewable, nonrenewable, replenishable, and cultivated natural capital. See, for example, Aronson and others (2007).

14. See Hediger (1997).

15. See Common (1997).

well be unfeasible.[16] This is further emphasized by Jackson (2016) who argues that even though there is historical evidence of relative decoupling, that is of a decline in the material intensity of economic output, absolute decoupling, defined as the situation where material use declines in absolute terms, remains so far a mirage, as CO_2 emissions keep increasing together with the overall material footprint of production (including mineral resources extraction).

As of today, there are continuing efforts made to integrate Nature within macroeconomic models. An example of such efforts is Kornafel and Telega (2020), who embedded natural capital intended as a renewable resource in a neoclassical growth closed-economy model to explore whether it is possible to sustain economic growth even if material consumption increases alongside.[17] They assume that produced goods and natural capital are complements in the sense that economic growth increases the material demand, which means greater depreciation of natural capital. They find stable equilibria when: (i) the stock of natural capital is large enough to begin with even if no investment in natural capital is made; (ii) the growth rates of capital and technological progress are strong enough given the assumed elasticity of material intensity of production relative to the elasticity of material intensity of technology; (iii) investments in natural capital are large enough to maintain the stock of natural capital at a level compatible with the complementarity requirements of continuous production given assumed technologies.

In a report prepared following an invitation from the Chancellor of the Exchequer of the UK government, Dasgupta (2021) proposed a similar but alternative modification to the model of economic growth that includes natural capital (alongside man-made and human capital), providing a complete capital theoretic account of human activities, from source to sink. In the global economy, natural capital features in an otherwise traditional production function in two forms: as a flow of extracted provisioning service (like oil, timber, fish etc.) and as a stock supplying ecosystem services which are essential to production (like carbon and nitrogen cycles, disease control, climate regulation, soil regeneration etc.)—a modeling device to capture the fact that "the human economy is embedded in the

16. See Ward and others (2016) and Parrique and others (2019).

17. In their model, which features no behavioral equations and no direct role for Nature in the production function, natural capital is distinct from the 'normal' renewable resource, which is intended only as a factor of production, because it plays a positive social function through the provision of recreational and similar services.

biosphere."[18] This setup is fully aligned with the ecological literature—to that effect, it assumes that the net regeneration rate of natural capital is bounded and, if natural capital falls below a certain limit (a "tipping point"), the economy collapses. It also assumes that ecosystem services are complementary to each other in certain ways, and this set bounds on the efficiency with which services from natural capital can be converted into output, implying that global economic growth is bounded. Optimizing agents demand goods produced using the various kinds of capital and value natural capital in their utility function. The main result of this analysis is that, when natural capital is assumed to have an intrinsic value, multiple stationary equilibria exist for different combinations of various types of capital (man-made, human, and natural), but these will depend on the current size of such stocks.

Dasgupta (2021)'s report marked a significant moment for ecological economics and macroeconomics more generally, as it put, for the first time, the issue of sustainable development and limits to growth front and center in the policy arena. The report sparked a wave of newly found interest, with networks and activities recognizing the essential role that Nature plays in economic systems (such as the *Network for Greening the Financial System*, bringing together central banks and financial supervisory institutions together on matters of green finance). The topic is undoubtedly gaining momentum with more policy organizations joining in the conversation, resulting in new landmarks such as the The Kunming-Montreal Global Biodiversity Framework and the establishment of international working groups focused on Nature-related risks to the financial systems.

Taking stock of these previous theoretical advances, in the next section we describe a novel model that was built to help policymakers evaluate the long-run effects of natural resources exploitation and conservation. The model is general enough to allow for a broad characterization of Nature and lends itself well to further fine-tuning and explorations.

2. Introducing Natural Capital in a Macroeconomic Model

In what follows, we proceed by presenting the work of Batini and Durand (2024), which introduces natural capital in a DSGE model

18. See page 144 in Dasgupta (2021).

of the type used to help inform policy analyses. We chose to keep the model-specific economic description qualitative, focusing instead on the quantitative aspects of Nature modeling with an emphasis on its integration within a macroeconomic model.

The framework assumes an infinite horizon in discrete time, with each period corresponding to five years, and a world economy composed of two blocs or regions. The framework assumes that Natural Capital (K_N) is unevenly distributed, displays critical thresholds or "tipping points" beyond which the ecosystem is irreversibly altered, and can contribute to the evolution of total factor productivity via an externality. Specifically, a larger stock of natural capital provides more abundant ecosystem services, which in turn expand the output that can be produced for each unit of labor and man-made capital, given the underlying rate of technological progress.

The two regions, Home (H) and Foreign (F), are populated by infinitely lived households and firms. The blocs trade with each other and differ in size and production structure. Importantly, only H is endowed with natural capital.[19] H produces both "green" and "brown" intermediate goods, which require natural capital as an input of production; both blocs must buy these goods to produce. Both blocs also produce final goods combining the purchased (and then aggregated) intermediate goods with hired labor and rented man-made capital. The technologies used to aggregate the intermediate goods and produce the final good are symmetric between the two regions. We assume that producing green goods (e.g., harvesting forest food) does not dent the stock of natural capital, while producing brown goods (e.g., extracting timber from a forest unsustainably) does. In this sense, the model is assuming that it is possible to "invest" in natural capital through ecosystem conservation, which basically requires ensuring that natural capital is protected from excessive extractive uses or man-made degradation.

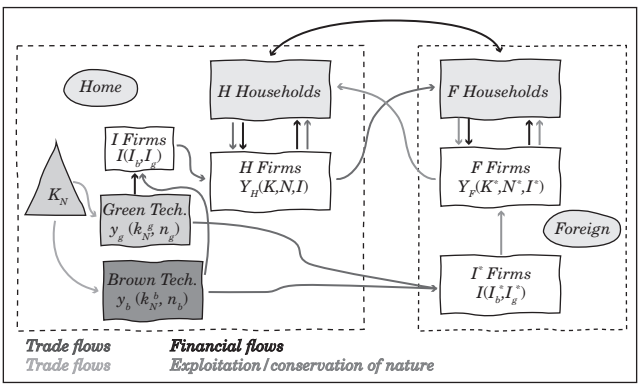
The model is free from nominal and real friction. Financial markets are complete. Finally, both blocs have a fiscal authority that collects taxes (distributes subsidies) and rebates the proceeds (collects the resources) lump-sum to (from) the households. Figure 1 graphically summarizes the structure of the model, showing the various agents and the (main) economic linkages among them. We refer the reader to Batini and Durand (2024) for a detailed algebraic description of the

19. This assumption is simplifying but helps mimic the world's uneven distribution of natural capital.

various economic relationships, together with the associated resulting optimality conditions.

In the next sections, we review how natural capital is modeled. In line with Dasgupta and Mäler (2004), D'Alessandro (2007), and Kornafel and Telega (2019), there are two basic alternative specifications: one with an exogenous and known critical threshold and one without a critical threshold. These two versions have a well-established tradition in the study of fisheries management[20] and conservation more in general,[21] and allow for conceptualizing the dynamic resource-harvesting problem that economic agents face when deciding how much of the natural resource to exploit for production and how much to keep in place for (possible) future use. We also review a third specification for Nature, which assumes that the critical threshold is unknown to the economic agents and is endogenous to the amount of natural capital depletion (that is, the probability of crossing the threshold increases as more natural capital is consumed and, in any given time, the agents do not know *ex-ante* whether a given depletion of resources is bound to set in motion the tipping point). We review each one of the three versions in turn below.

Figure 1. Diagram of the Two-Bloc Model



Source: Batini and Durand (2024).
Notes: The figure shows a stylized representation of the two-bloc model of Batini and Durand (2024). Starred variables refer to F bloc variables. K refers to physical capital; N, n_g, n_b refer to labor employed by the final good and intermediate goods sectors, respectively; I refers to the intermediate aggregate good; y_b, y_g refer to the intermediate brown and green inputs; Y_H, Y_F denote the final H, F produced output; K_N is the stock of Nature.

20. See Clark (2006).
21. See Clark (2010).

2.1 Natural Capital with no Critical Threshold

In the first version, the stock of natural capital can always recover to its original carrying capacity level, no matter what amount of depletion occurs between periods. In particular, in this version, the beginning-of-period stock of natural capital ($K_{N,t}$) depends nonlinearly on its "background" or "natural" regeneration rate, which in turn depends on how far the existing stock is from its carrying capacity level CC, as well as on the amount that is exploited for production:

$$K_{N,t+1} = K_{N,t} + r_N K_{N,t}\left(1 - \tfrac{K_{N,t}}{CC}\right) - K^b_{N,t}, \tag{1}$$
$$A_{N,t} \equiv r_N K_{N,t}\left(1 - \tfrac{K_{N,t}}{CC}\right)$$

where r_N is a parameter denoting the intrinsic regeneration rate, and $K^b_{N,t}$ refers to the amount of natural capital that is destroyed and used as an input in the production of the brown intermediate goods. We call the rate at which natural capital accumulates (or decumulates) through the impact of its own regeneration, given the beginning-of-period existing stock the *Accumulation rate* ($A_{N,t}$). It is important to note that, given this specification, the rate of accumulation also depends on the carrying capacity, CC, and that the rate of accumulation diminishes as the stock of natural capital approaches CC.

2.2 Natural Capital with an Exogenous and Known Critical Threshold

Since the ability of natural capital to recover may change when natural capital is less than a certain Critical Threshold (CT), we also consider a second version of the general specification, which makes the evolution of natural capital dependent on such threshold. Assuming that the level of CT is fixed and known to the agents in the economy, the equation for natural capital under this specification becomes:

$$K_{N,t+1} = K_{N,t} + r_N K_{N,t}\left(1 - \tfrac{K_{N,t}}{CC}\right)\left(\tfrac{K_{N,t}}{CT} - 1\right) - K^b_{N,t} \tag{2}$$
$$A_{N,t} \equiv r_N K_{N,t}\left(1 - \tfrac{K_{N,t}}{CC}\right)\left(\tfrac{K_{N,t}}{CT} - 1\right),$$

In this case, once $K_{N,t} < CT$, the existing stock of natural capital converges progressively to zero (an "environmental disaster" that would not allow life on earth). In other words, in the presence of a

critical threshold, the rate at which natural capital accumulates/decumulates depends not only on CC and r_N but now also on CT.

2.3 Natural Capital with an Endogenous and Unknown Critical Threshold

In our third, more realistic, specification for the evolution of natural capital we assume that i) the level of the CT is unknown to the agents of the economy, and ii) that crossing the CT does not imply a complete progressive depletion of natural capital but rather a permanent re-adjustment of its carrying capacity, towards an impaired, lower level.

This idea reflects the fact that, in environmental sciences, the level at which a tipping point is reached is typically unknown, but it is observed that crossing a tipping point usually switches the ecosystem into a possibly stable but less productive and/or healthy state. The case of the Atlantic rainforest is in point, in the sense that, as shown by research, the forest itself, when in a self-sustainable state, can recycle much of the rain that falls on it, generating a self-preserving cycle. Research suggests that removing as little as 30 percent of the forest cover can impede this self-perpetuating stabilizing cycle. Without this active restoration system in place, the system could flip to another state, such as a savannah grassland.[22] The specification that we adopt is reminiscent of the modeling of tipping points in climate change.[23] In our case, however, regime shifts are triggered by a reduction in the stock of Nature below a certain tipping point level. In particular, we assume that, conditional on not having crossed a tipping point at time t, there is a probability $h(K_{N,t}, K_{N,t+1})$ of crossing that point between time t and $t + 1$, depending on the stock of natural capital that is left after exploitation occurring at time t.

Formally, at the beginning of time t, conditional on not having crossed the threshold yet, the evolution of natural capital is uncertain.

$$\begin{aligned} K_{N,t+1} = {} & \left[1 - h\left(K_{N,t}, K_{N,t+1}\right)\right]\left(1 + r_N\left(1 - \tfrac{K_{N,t}}{CC}\right)\right)K_{N,t} \\ & + h\left(K_{N,t}, K_{N,t+1}\right)\left(1 + r_N^0\left(1 - \tfrac{K_{N,t}}{CC_0}\right)\right)K_{N,t} - K_{N,t}^b \end{aligned} \tag{3}$$

where $h(\bullet)$ denotes the probability of crossing the critical threshold between periods, CC is the current level of carrying capacity, and

22. See Nepstad and others (2007), Salati (1987), Farley (2008).
23. See Lemoine and Traeger (2014).

CC_0, r_N^0 are the alternative levels of carrying capacity and intrinsic regeneration rate towards which the system adjusts if the critical threshold is crossed. In the above expression, $K_{N,t+1}$ reflects uncertainty as of time t, its actual value only being revealed at the beginning of time $t + 1$, depending on whether the threshold has been crossed or not, given the exploitation/conservation choices made as of time t. In the following discussions, we will always assume that $CC_0 \leq CC$ and $r_N^0 \leq r_N$, meaning that activating the tipping point can reduce the carrying capacity of Nature, and/or its intrinsic regeneration rate.

The probability of crossing the threshold, which we call the *hazard ratio,* is endogenous and given by

$$h\left(K_{N,t}, K_{N,t+1}\right) = \max\left(0, \frac{max\left(K_{N,t+1}, \overline{K}_N\right) - K_{N,t}}{\overline{K}_N - K_{N,t}}\right) \tag{4}$$

where $\overline{K}_N$ corresponds to the level of K_N at which point crossing happens with probability 1.[24] This expression defines the hazard of crossing. As the economy consumes more stock of natural capital without crossing the threshold, the agents infer that the tipping point is somewhere below the current stock of natural capital. Importantly, as more depletion occurs, the probability of crossing increases. In this scenario, the critical threshold is unknown, and could be well above: in fact, every level of natural capital between $K_{N,t}$ and the value of $\overline{K}_N$ has an equal chance of being a critical threshold (e.g., the critical threshold is uniformly distributed between the initial existing stock of natural capital and $\overline{K}_N$).

2.4 Accumulation Rates

To help understand what these alternative specifications entail for K_N in practice, Figure 2 plots the rate at which natural capital evolves (that is, its accumulation rate A_N) with or without CT, normalizing the value of CC to 1.[25] In line with the above discussion, the figure shows that, in the absence of a critical threshold, the accumulation rate of natural capital is always positive and increases before decreasing

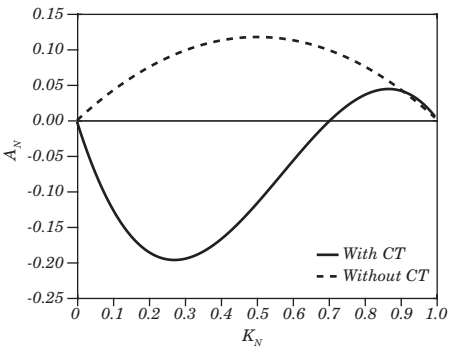
24. In a simpler specification it would be possible to consider the $h(\bullet)$ as exogenous, while still capturing the uncertainty associated with crossing the critical threshold.

25. The case with an endogenous CT is similar to the case without a CT since both the pre-tipping and post-tipping natural capital dynamics follow the specification assumed in the model without a CT.

in proximity of natural capital's maximum sustainable level, CC—namely, A_N is always above zero in the interval (0, 1), increasing for $K_N < CC/2$ and decreasing for $K_N > CC/2$. Conversely, in the presence of a critical threshold, A_N is negative for values below CT, but positive and increasing for a range of values between CT and CC before converging to zero as K_N approaches CC.

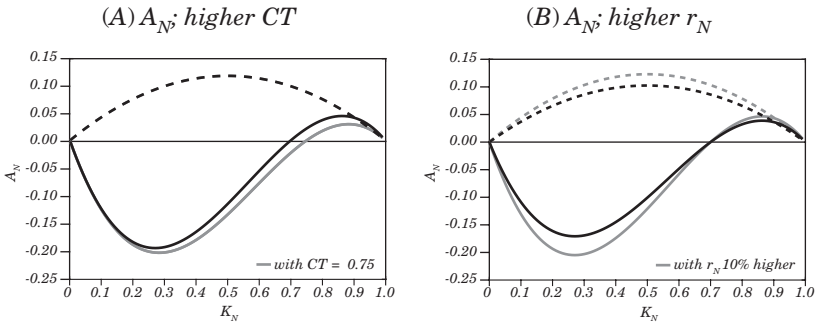
It is instructive to compare how the accumulation rate changes depending on the assumed values of the CT and regeneration rate, r_N, both of which are assumed exogenous and fixed in the setup. To this end, panel (A) in Figure 3 shows that a marginally higher critical threshold compresses the region where there is positive accumulation of K_N and impairs the regeneration rate when K_N is close to the CT, while panel (B) evidences an upward shift in A_N following an increase in r_N.

Figure 2. Nature Accumulation Rates (A_N)



Source: Authors' calculations.
Notes: $CC = 1$, $CT = 0.7$. $r_N = 1.4$ when assuming a CT, and $r_N = 0.4$ otherwise.

Figure 3. Nature Accumulation Rates (A_N) Counterfactual



Source: Authors' calculations.
Notes: Note: In the baseline, we set CC = 1, CT = 0.7. r_N = 1.4 when assuming a CT, and r_N = 0.4 otherwise. In counterfactual (A), CT = 0.75, while in counterfactual (B), r_N is increased by 10%. Counterfactuals are shown with grey lines.

2.5 Adding Uncertainty over the Regeneration Rate

In practice, under all three scenarios, the accumulation rate of natural capital remains uncertain because parametric shocks to each specification may affect the evolution of natural capital. To capture this, we go one step further in modeling K_N and postulate that there are shocks that affect multiplicatively the accumulation rate. Specifically, we define a stationary shock process:

$$ln\left(z_{t+1}\right) = \rho^N \, ln\left(z_t\right) + \sigma_\epsilon \epsilon_{t+1} \tag{5}$$

where $\sigma_\epsilon > 0$, $|\rho^N| \leq 1$ and $\epsilon_{t+1} \sim N(0, 1)$. We thus rewrite the law of motion of natural capital (in the absence of a critical threshold) as:

$$K_{N,t+1} = K_{N,t}\left(1 + z_t r_N \left(1 - \frac{K_{N,t}}{CC}\right)\right) - K^b_{N,t}, \tag{6}$$

We adopt the same approach when modeling natural capital in the presence of a critical threshold (both exogenous and endogenous). The multiplicative assumption implies that the greater A_N, the larger the uncertainty that the agents (or social planner) face when making optimal decisions, due to the higher impact that the shocks can have. Importantly, the (log) formulation of the shock implies that the accumulation rate cannot turn negative following the realization of a bad shock. This implies that it is always possible to compress exploitation of Nature enough so as to gradually allow

Nature to recover following a bad shock, even if close to the *CT*. This is a simplifying assumption, which we adopt to contain the studied equilibria within the economically sustainable region (to the right of the *CT*).

2.6 Optimal Management of Renewable Resources

The macroeconomic model (which we will also refer to as a "bio-economic", or Nature-economy model equivalently), once appropriately calibrated, can be used to analyze the optimal management of renewable natural resources. We refer the reader to the original paper for a discussion of the calibration and associated challenges. To streamline the presentation, in the following discussion, we omit possible externalities from the stock of Nature, meaning that the analysis can equally apply to a competitive equilibrium allocation or a social planning problem.[26]

Batini and Durand (2024) highlight that there are significant differences in economic and natural dynamics depending on whether the initial stock of Nature is abundant or not and also on whether Nature´s evolution is influenced by the existence of a critical threshold. A main result is that in the case of an initially quasi-pristine environment, and independently of the existence of a *CT*, it is always optimal to gradually decrease the stock of Nature. However, there are differences regarding the final steady-state level at which the economy converges in the long run. This happens because otherwise a large portion of K_N must be kept aside for conservation, which in turn implies reducing substantially the production of brown goods both presently and in the future, and brown goods are the dominant input in the production structure of the economy of aggregate intermediate goods. Importantly, the tradeoff between conservation and exploitation becomes larger as K_N is closer to its *CC* because, as K_N approaches its pristine level, the rate at which K_N accumulates if left untouched approches zero (even more, for levels of K_N above *CC*, it turns negative). In fact, for a level of $K_N = CC$, there is no natural regeneration, absent human interventions. This means that, to conserve the full stock of Nature, there should not be any level of brown production, an outcome

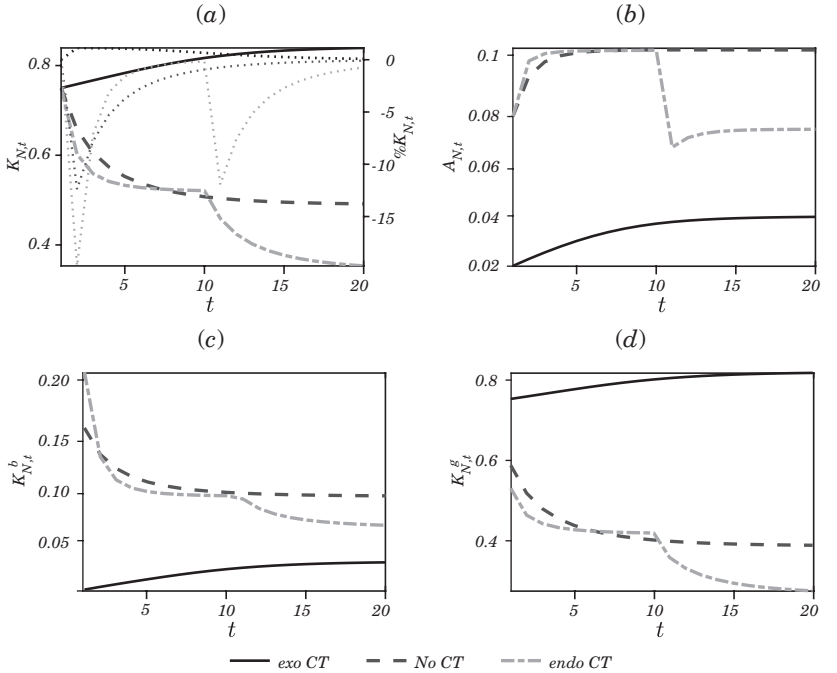
26. The possibility of externalities from the stock of Nature opens the door to a study of economic policies as the social planner and competitive equilibrium allocations would then differ; we refer the reader to the original paper for an exercise that involves subsidizing green production, including a welfare analysis.

that is clearly incompatible with life on earth. Starkly different results appear when an economy starts with a stock of Nature very well below its pristine level and possibly close to its (exogenously given) CT (when assumed). Figure 4 summarizes how K_N should be optimally managed in this case over the long run (we report the first 100 years), contrasting the three ecological modeling choices presented in the previous sections and assuming $K_{N,t0} = 0.75$, with an exogenous CT level equal to 0.7. The latter value is aligned with ecological findings—for instance, while some scientists go as far as to argue that already a 10 percent loss in biodiversity might be considered unsafe,[27] others are much less pessimistic, setting safe limits as low as 30 percent of the original biodiversity richness,[28] which is what we are going to assume moving forward.

Specifically, when assuming an exogenous CT, it becomes optimal to gradually conserve more natural assets than when the economy starts in an abundant K_N state. Incremental additions to K_N then allow for *both* more exploitation and conservation (K_N^b, K_N^g, respectively). A result of Batini and Durand (2024) is that, as the economy moves away from the CT, brown output can expand allowing for an overall increase in consumption through time from the initial levels. This happens because, with K_N initially close to CT, it is optimal at first to reduce brown output and divert labor resources to green production in order to raise the level of K_N from its critically depleted state. But as the economy moves away from its tipping point, it becomes increasingly inefficient to sacrifice brown production to favor green production, which only has a marginal role in total production. Despite this relocation of labor resources away from the green sector, the overall rate of decline in green production is muted, which is possible because when moving away from CT the rate at which Nature can regenerate itself increases, thus raising the endogenous accumulation rate, which in turn allows to count on more natural capital in the future while still allowing for more K_N accumulation in the near-term (as also shown in the top right panel of Figure 4).

27. See Newbold and others (2016).
28. See Steffen and others (2015).

Figure 4. Optimal Evolution of Natural Capital



Source: Authors' calculations.
Notes: $CC = 1$, $CC_0 = 0.7$, $r_N = r_N^0 = 0.4$. When modeling the case with an endogenous CT, we assume that the threshold is crossed over at $t = 10$. In the shown simulations, realizations of the shocks are set to 0.

When considering the case of an endogenous and unknown tipping point, the results are aligned with those from the model without CT, albeit with two major distinctions, as also highlighted in Figure 4.[29] First, the possibility of crossing the tipping point makes it optimal to eventually converge to a steady-state value of K_N, which is relatively higher as compared to the one in the simple model without a CT.[30]

29. We fix the lower threshold of the tipping probability, $K_N = 0.4$, a relatively low value. This parametrization implies that starting from a level of $K_{N,t0} = 0.75$ a 10% reduction of natural capital is tantamount to an approx. 21% probability of moving to the low-carrying capacity world.

30. Even though the initial drawdown is relatively stronger, since agents do not know which regime will be in place in the next period, and in case the post-tipping scenario materializes, having conserved too much Nature as compared to what is technologically efficient is costlier the farthest away from $CC_0/2$—the level at which the accumulation rate is maximized—the stock turns out to be.

Second, if the tipping point is crossed during the transition to the long-run steady state (which in the figure is assumed to happen at $t = 10$), the accumulation rate drops, as the law of motion of K_N is now regulated by CC_0 with $CC_0 < CC$ (we assume that $r_N = r_N^0$ for simplicity). This, in turn, contributes to an initially strong drawdown of Nature starting at $t = 11$, until convergence to the lower long-run stock compatible with the post-tipping carrying capacity level. This latter result arises because the carrying capacity in the post-tipping world is below that of the pre-tipping environment, so that the level of K_N that maximizes the accumulation rate is also relatively lower.

Having described how natural capital should be efficiently managed under our three alternative specifications, a further interesting question is the role that uncertainty plays in our setup. Up until now, the discourse assumed that all realizations of the shocks were equal to zero, which is convenient when emphasizing long-run dynamics, but this does not need to be the case. In truth it is more realistic to assume that the realizations of the shocks are different from zero, making the accumulation rate respond to nonmodeled factors, following the specification in Equation (5). This latter dynamic assumes that $\rho^N = 0.95$, a fairly high value which underscores that environmental events might have large persistence over Nature's future evolution.

We then propose the following exercise: the economy starts with a stock of Nature close to its exogenous CT (if assumed) and experiences a sequence of (positive and negative) shocks (ϵ_t), starting with a negative shock at $t = 2$. This means that z_t, which regulates the intrinsic regeneration rate of Nature, falls below 1 at $t = 2$. The shock, while not pushing the ecological system beyond the tipping point (by construction—see our discussion on uncertainty), still incapacitates Nature's ability to regenerate itself over time. How, then, does the evolution of consumption differ from a scenario where all shocks are set to zero, especially with regard to the case where there is an exogenous CT?

Figure 5 summarizes the simulations from this exercise, showing the impacts on consumption, green labor, and the accumulation rate of K_N. Dashed lines represent the scenario where all realizations of the shocks are zero, while solid lines refer to the case where shocks can vary over time. Macroeconomic variables are expressed in percentage deviations from their initial (t_0) levels. As discussed above, the optimal management of K_N leads to a gradual increase in

consumption (independently of the presence of a *CT*) and a gradual increase (decrease) in green labor in the scenario without (with) a *CT*.[31]

Importantly, the figure also illustrates that when introducing a negative shock to z_t, the presence of a *CT* requires keeping consumption approximately constant at its initial level. This happens because the agents are efficiently conserving more Nature and also shifting more labor resources to the green sector (as also highlighted in the figure by the smaller decline in green labor, as compared to the scenario without shocks), which however contributes much less to the production of the final home goods.

We repeat the exercise, this time comparing the case without a *CT* together with the case where there is an endogenous and unknown *CT*, which, in this case, is never crossed over throughout the simulation. Hence, in both scenarios, the underlying ecological process of Nature remains the same over time. Figure 6 summarizes the results, which highlight how the possibility of crossing the threshold dramatically changes the efficient evolution of consumption and labor dedicated to the green sector, over the next 25 years (e.g., five periods in the model). In particular, while in the absence of a *CT* it is efficient to sustainably increase consumption for several periods, as more Nature is exploited, this is no longer the case when agents rationally internalize that more exploitation increases the probability of tipping over the edge of Nature. This is also well reflected in the difference in accumulation rates, which shrinks as the economy precautionarily settles over time at a steady state further to the right of $CC/2$ (the stock of Nature that maximizes the ecological accumulation rate, as also shown in Figure 2).

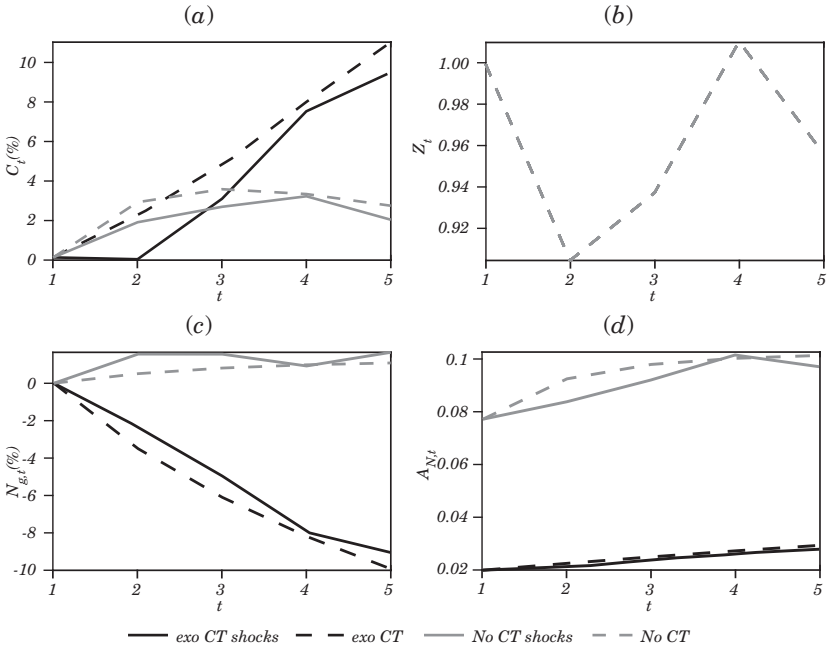
3. Studying the Green Transition using the Bio-Economic Model

The analytical framework presented in this chapter can be used as a foundation to a multitude of analyses and exercises. In particular, central banks and other policy institutions can benefit from a deeper understanding of how nature degradation interacts with the financial system and the economy at large,[32] especially with an eye on the green transition.

31. The gradual (but temporary, as suggested by the figure, showing a reversion starting in period 5) increase in consumption in the no-*CT* scenario arises because the speed of physical disinvestment is faster than the speed at which output declines, which in equilibrium allows for greater consumption.

32. See ECB (2023).

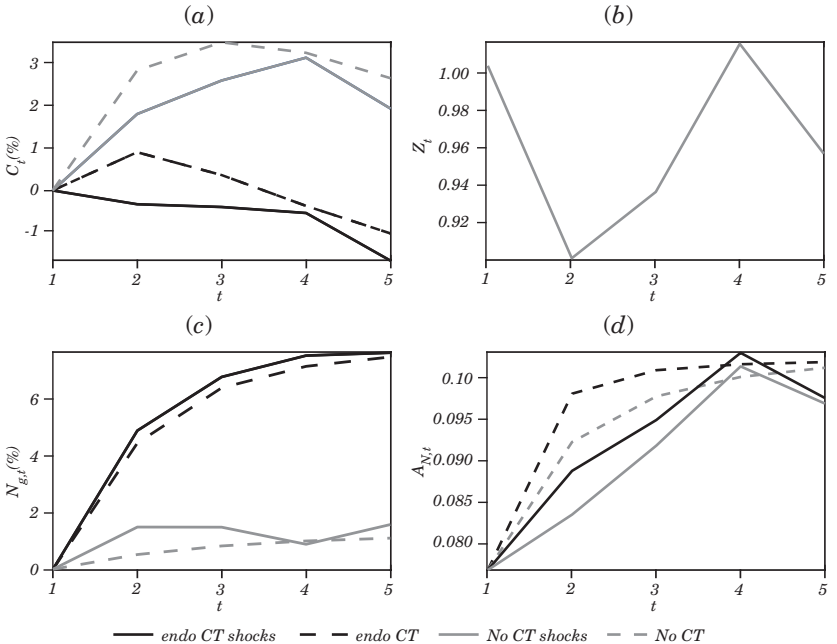
Figure 5. Evolution of Selected Variables



Source: Authors' calculations.
Notes: $CC = 1$, $CT = 0.7$, $K_{N,t0} = 0.75$. Light solid (dashed) lines refer to the *No-CT* case with (without) shocks, while dark solid (dashed) lines refer to the *CT* case with (without) shocks. Each macroeconomic variable is expressed in terms of the percentage change with respect to its initial level at $t0$. The variable $N_{g,t}$ refers to labor employed by the green sector, and the variable C_t to consumption.

This section builds on the previous discussions and results and summarizes how the bio-economic model just presented can be adapted for such purposes. The green transition should be understood as a gradual shift toward an economy that is less based on over-exploitation of natural resources and that instead relies relatively more on sustainable activities aligned with the concept of the circular economy, including the adoption of polyculture and regenerative land and ocean farming, conservation activities, and sustainable forest management. We will structure our discussion of the transition around three broad thematic analyses, namely, the short-run macroeconomic impacts on quantity and prices, the importance of distinguishing between local versus global environmental policies, and the structural shifts in preferences, technologies, and mutating ecological dynamics that will arise along the way.

Figure 6. Evolution of Selected Variables



Source: Authors' calculations.
Notes: $CC = 1$, $CT = 0.7$, $K_{N,t0} = 0.75$. Light solid (dashed) lines refer to the *exo-CT* case with (without) shocks, while dark solid (dashed) lines refer to the *endo-CT* case with (without) shocks. Each macroeconomic variable is expressed in terms of the percentage change with respect to its initial level at $t0$. The variable $N_{g,t}$ refers to labor employed by the green sector, and the variable C_t to consumption.

3.1 Short-Run Macroeconomic Effects of a Green Transition

As ecological systems degrade, supply-side disruptions are expected to become more frequent, generating potential uncertainty that economic forecasters and policymakers need to take into account when making decisions. Ecological phenomena in particular are increasingly being considered as relevant drivers of output loss and inflation, for example through droughts that cause a reduction in agricultural output.[33] As stressed by the World Bank, the economic cost in terms of GDP loss due to a partial collapse of ecosystem services would be large, with the majority of countries in the analyzed sample potentially

33. See Barnes and Bosch (2024).

suffering an economic decline larger than that caused in 2020 by the Covid-19 lockdowns.[34] From an economic policy perspective, these predictions point to far-reaching effects via economic and financial markets. One example in this direction is Burke and others (2025), who propose analyzing how ecological collapse can affect sovereign borrowing through changes in credit ratings. Another case in point is Pinto-Gutiérrez (2023), who documents that droughts increase mining companies' loan spreads and influence financial institutions' premiums on loans granted to mining companies. Similarly, Giglio and others (2023) find that the returns of an equity portfolio long in industries with low biodiversity risk exposures and short in industries with high biodiversity risk exposures is positively correlated with an aggregate index of biodiversity risk, which suggests that financial markets participants are pricing in the risk of ecosystem degradation when valuing companies.

On the monetary front, while there is uncertainty over the final qualitative impact on headline inflation (for example, because risk-adverse consumers might cut back on consumption when faced with more frequent environmental shocks, which partly compensates price pressures), there seems to be a consensus that worsening ecological dynamics do lead to an increase in price variability.[35] From a monetary policy perspective, some of the challenges that are usually discussed in the context of climate change are also relevant when looking at biodiversity losses; specifically, central bankers need to adapt their toolkits taking into account the impact of physical risks and transition risks on the conduct of monetary policy. For example, changes in the natural interest rate, which could be falling in the context of lower productivity and increased risk aversion, might reduce the space for conventional instruments used when fighting inflation. Also, supply shocks that lower economic activity while increasing prices might worsen the typical tradeoff with price stability.[36] In this context, it is reasonable to argue that, even from a strictly financial standpoint, a gradual shift away from carbon-intensive activities that exacerbate the effects of natural hazards and extreme weather events is justified.[37]

34. See World Bank (2021).

35. See Ciccarelli and others (2023).

36. The NGFS Macroeconomic Modeling Handbook (NGFS, 2024) presents a comprehensive survey on how economic frameworks, including neoKeynesian setups, should adapt to take into account these challenges in the context of climate change.

37. See Saco and others (2021).

The two-bloc Nature-economy model provides a useful platform to analyze these issues at large. For instance, introducing nominal stickiness as in Calvo (1983) could be easily done by assuming that the brown and green intermediate inputs are characterized by monopolistic competition, giving rise to some degree of price rigidity. Also, some degree of nominal wage stickiness could be assumed, as done for example, in García and others (2019). Importantly, the distinction between intermediate green and brown inputs allows to capture that the prices of the latter are generally relatively less sticky than those of the former[38] and also the imperfect substitutability of both inputs for production of the final consumption goods. This is essential since, when inputs cannot be freely substituted for, there is a tradeoff from transitioning, as brown taxes do increase marginal costs for the rest of the economy. In particular, price rigidity combined with downward rigidity in nominal wages can lead to a "green-transition-led" recession. The recession is deeper when an inflation-targeting central bank reacts to the increase in headline and core inflation, both of which tend to increase. According to Del Negro and others (2023), these dynamics are however short-lived to the extent that the central bank does not respond to the increase in inflation and remains committed to closing the output gap, arguably without a loss in credibility. These macroeconomic effects seem supported also by empirical analysis[39] and other modeling work,[40] even though further analysis is needed in the context of emerging and developing countries, where monetary policy frameworks are on average relatively weaker[41] and where deviations (albeit temporary) from an inflation-targeting regime coupled with a drop in local economic activity might give space to instabilities and nonlinear effects, via capital flows.[42]

In the Nature-economy model, the possibility of a tipping point further adds a layer of complexity to the analysis since the closer the economy is to its ecological critical threshold, the lower the accumulation rate of Nature. This means that if, when transition policies are first introduced (for example via a tax on brown activities), the economy is close to its *CT*, one of the factor inputs (Nature) cannot change much despite shifting sectoral demand for green goods. This is a simple point, yet it has important implications.

38. See Del Negro and others (2023).
39. See Konradt and Weder di Mauro (2023).
40. See Olovsson and Vestin (2023).
41. See IMF (2023).
42. See Batini and Durand (2021).

In fact, in the limit, the natural production factor is fixed, since as shown in Equation (2), $limK_{N,t \to CT} A_{N,t} = 0$, that is, the accumulation rate goes to zero. One important implication is that this impairment in the capacity of Nature to grow in the short-term also reduces the scope for greater productivity enhancements that would otherwise be expected to materialize through a reduction in any pre-existing negative externality on productivity.

From an economic standpoint this implies that, for a given level of productivity, the closer the economy is to $A_{N,t} = 0$, the greater the amount of labor that needs to shift from the brown and final consumption goods sectors to the green intermediate sector in order to reach a certain level of production of green goods (and under usual assumptions regarding production, such as constant returns to scale, we know that the marginal product of labor, for a given fixed amount of the other factors inputs, is decreasing). Of course, at the optimum, there is a tradeoff which balances the decrease in the production of H and b intermediates (from lower labor dedicated to these sectors and also less exploited natural resources) against the marginal costs from keeping the g intermediate production at its pre-transition level. In equilibrium, the tradeoff determines the efficient decline in the production of the aggregate intermediate input that maximizes economic welfare. Overall, these nuances suggest that in the bio-economic model, the "policy-induced" recession might be more protracted in time if implemented too late (that is when the economy is already reaching its tipping point) and when not accompanied by changes in technology and/or production paradigms that reduce the reliance on brown inputs, as we will further explore below.

3.2 Global Policies, Local Policies, and Political Economy Considerations

The overall economic effect of a green transition on the world economy also depends on whether the policies are enacted globally or locally, and also on how each (local) authority responds to other authorities, including on whether there is some degree of policy coordination across the various regions of the world. The bio-economic model is rich enough to make all these distinctions and carry out a comprehensive analysis. For instance, global policies could be introduced *via* a tax/subsidy on all intermediate brown production, while local policies could be modeled via a tax/subsidy on brown imports that are purchased by the foreign bloc (or similarly on brown

goods that are purchased by the home bloc). Policy coordination could be easily introduced, assuming that each bloc either sets the tax/subsidy as a Nash equilibrium outcome (for example, via a National Social Planner), taking as given the other bloc's policy, or instead as a solution to a worldwide planning problem where a single social planner sets the optimal instruments.

While existing climate economy models emphasize that emerging markets, being the major producers of brown (CO_2-emitting) goods,[43] are unlikely to initiate by themselves sufficient climate and environmental policies,[44] our setup allows for a more pragmatic discussion of the issue. In particular, by underscoring the dual use of the stock of Nature—as an input required to carry out exploitative activities and also as an input in conservation activities—our model suggests that it is possible for emerging markets to (at least in part) shift their prevailing economic modes of production toward sustainability without necessarily compromising long-run economic development. In fact, our framework suggests quite the opposite, which is that it is more efficient to start out implementing the policy when the stock of Nature is still abundant, permitting an alignment between private and social marginal values from the get-go, rather than in an environment where a previously inefficiently high production of brown goods ultimately led the economy relatively closer to a tipping point. Then it requires reorienting a relatively larger amount of resources toward the green sector, to avoid crossing the *CT*. Importantly, crossing the *CT* is not optimal as it puts in motion a decline in the natural stock independently of what economic policies are implemented thereafter (that is, in our framework, both tipping-points specifications are built following a "point of no return" paradigm). In this sense, as compared to traditional climate economy models where small countries/regions might see higher temperatures as exogenous to domestic environmental policies, our model infuses a local, self-interested, rationale to enact green policies sooner rather than later (or never).

Our assumption that it is possible to produce goods and services without harming the environment is backed by solid evidence and increasing support from policymakers. As an illustrative example, consider the case of Virunga National Park located in the Democratic Republic of Congo, and which dedicates resources to conservation efforts. Virunga's estimated total annual economic value in 2013,

43. See Cole and others (2021).
44. See Minesso and Pagliari (2023).

despite the significant fragilities afflicting the country, was approximately USD 48.9 million, 41 of which correspond to direct-use values such as fisheries and tourism.[45] According to the same report, in a stable situation conducive to economic growth and tourism, the park's total economic value could be higher than USD 1.1 billion per year and could be the source of more than 45,000 jobs. Several other examples in more stable geographic regions confirm the vast economic potential that derives from the sustainable use of the stock of Nature.[46] In another case in point, demonstrating the strong support that conservation is attracting among policy institutions, the European Investment Bank argues that investing in forests can enhance economic growth in rural communities.[47]

Distinguishing between the geographic location where green policies are enacted is also fundamental from a political economy standpoint. For instance, advanced economies' push to introduce sustainability requirements affecting international trade (via for example carbon border adjustments) and also their objective to swiftly and rapidly embark on a net zero transition[48] might be perceived as an example of "regulatory imperialism", which could ultimately lead to a worsening of trade relationships and less willingness to embrace sustainability as a long-term development paradigm. As an example of such brooding attacks, Almeida and others (2023) argue how the European Green Deal should be interpreted as "a regime imbricated in colonial and neocolonial motivations viewing peripheral countries and societies as policy deficient, climatically unambitious, and in need of 'capacity-building' for sustainability and development". Along the same lines, Zografos and Robbins (2020) underscore that, despite its good intentions, the Green New Deal will generate new "sacrifice zones", meaning geographic areas in the Global South that will be negatively affected by "the sourcing, transportation, installation, and operation of solutions for powering low-carbon transitions, as well as end-of-life treatment of related material waste". In fact, aside from the rhetoric, mounting evidence suggests that it is already happening, as convincingly documented by Pitron (2020) for the case of China (for example, in the Nancheng county, Jiangxi province). In a similar vein, Meijaard and others (2020) discuss the role of palm oil, from which the

45. See WWF (2013).
46. See Chidakel and others (2020).
47. See EIB (2022).
48. See Almeida and others (2023).

majority of biodiesel is produced, in deforestation, suggesting that oil palm expansion directly contributed to regional tropical deforestation with values ranging from 3 percent in West Africa to 50 percent in Malaysian Borneo. As a result, several once populous species, including the orangutan, the tiger, and the white rhino, have become critically endangered.

In parallel to these concerns, other critics argue that some of the green actions and frameworks embraced by the North are no more than a *façade*: firms' practical actions deviate from their Environmental and Social Governance (ESG) disclosures, environmental tax reform significantly increases greenwashing of highly polluting companies, and firms facing rising tax costs associated with environmental standards tend to reduce green innovation.[49] All this seems to suggest that studying sustainability and finding solutions that emphasize "the local" rather than "the global" side of the equation could be given more prominence and might ultimately prove to be of great effect in shaping tomorrow's world.

3.3 Long-Run Structural Changes of a Green Transition

A realistic analysis of a green transition should account for the fact that, as time passes, the very foundations of our production system are also evolving. A similar argument applies in the case of the natural world, whose dynamics are endogenously mutating depending on the ecological pressures exerted upon it. Unfortunately, current macroeconomic research generally sidesteps these realities and tends to assume that, while technology might mutate and policies might change, the foundations of the economy are immutable.[50] In technical terms, this happens because standard DSGE models assume that the policy functions, which map the states of the economy (and of the natural world) to the actions of the agents within the model, are stationary; that is, there is time homogeneity in the Markov decision functions. Of course, this class of models could be adapted without resorting to a nonstationary framework by simply gluing together a sequence of stationary model simulations, one for each period of time, and solving each one of these fundamentally different models one by one, independently of one another. While this shortcut allows

49. See Hu and others (2023).

50. See Airaudo and others (2023), Olovsson and Vestin (2023), Konradt and Weder di Mauro (2023).

to construct, by connecting each decision function, a time path of optimal choices that are specific to the structure of the economy in each period, it would still neglect the connections that exist between different time periods, including uncertainty and anticipatory effects, which are arguably essential to an analysis of the transition.[51]

In this respect, our framework innovates as compared to the majority of the existing macroeconomic literature in the sense that it can be easily extended to allow for both uncertainty and time-dependent scenarios, both of which are required to represent economic and natural nonstationary changes. The reason behind such flexibility is that the bio-economic model solution technique directly borrows from Maliar and others (2020), which assumes time-inhomogeneous (nonstationary) policy choice functions. Different from the time-homogeneous model, where all parameters are time invariant and known to the agents since the beginning of time, in our setup, scenarios can be time-dependent and future values of the parameters unknown to the agents, or known only up to a certain probability. In the next paragraphs, we review two relatively easy examples that could be integrated into the bio-economic model to better represent real-world dynamics.

The first example assumes that the law of motion of natural capital is subject to state-dependent shocks. In this case, we could consider that σ_ϵ (or ρ) in Equation (5) is time-varying. Instead of modeling the volatility parameter as an ARCH process,[52] it could be assumed that, as the stock of Nature approaches the *CT* of the economy, the variability in the size and persistence of the shocks associated with the regeneration rate becomes larger due, for example, to more frequent and large extreme natural events.[53] This modeling would strengthen the argument to reduce natural capital exploitation, since as the economy embraces more sustainable means of production and moves away from its *CT*, the ecological process of accumulation becomes over time more stable and less subject to serpentine changes. This might have relevant welfare implications for developing and poor countries where climate risk insurance is often lacking or insufficient.[54]

Another direct example is the case of structural economic changes and/or technical advancements. This could involve a shift in the

51. See Fried and others (2022).
52. See Bollerslev and others (1994).
53. See Silva and others (2023).
54. See Madaki and others (2023).

parameters regulating the share and/or the elasticity of substitution between green and brown intermediate inputs. As a practical example, consider the share of green intermediate goods that are used to produce the final inputs—let's call it $\omega_{G,t}$. This parameter can gradually increase as time passes and also make sudden jumps. This evolution could be anticipated or not, and could also be embedded within a Markov transition matrix, with exogenously given probabilities. The simulated paths could reflect changes in policies, technological changes, or shifting preferences (for instance, agents might become more sensitive to sourcing sustainably produced inputs that originate from polyculture and regenerative land and ocean farming, conservation activities, and sustainable forest management).

A more sophisticated version of the Nature-economy model could naturally endogenize such dynamics along the lines explored in Acemoglu and others (2012), where it is assumed that the economy has "scientists" who can move across sectors and, through their discoveries, improve sector-specific productivity. A limited number of available scientists reflects that an improvement in technology in one sector comes at the expense of the other sector, generating a tradeoff (a direct manifestation of scarcity).[55] Technological advancements could allow for economic activities such as textiles, manufacturing, and real estate to reduce their use of virgin materials (for example, through renewable energy production, recycling of material inputs, etc.), thus expanding the potential of a circular economy. Also, while all energy production, including green energy, requires at its origin the exploitation of Nature, new technologies could lower the associated environmental pressure. For example, in the case of the infrastructures needed to produce green energy, which rely on rare earth minerals, new extraction and separation techniques might eventually become less taxing on the environment.[56,57] In modeling terms, this could result in final goods output that is generated by a relatively larger share of green (i.e., nonnatural capital depleting) inputs as opposed to brown inputs. To this end, $\omega_{G,t}$ could be assumed to be an affine function of the level of green technology in place, mimicking what is done by Antosiewicz and Kowal (2016) in the context of sectoral physical capital investments.

55. An equivalent approach is to assume a "technology" menu as in Hassler and others (2021).

56. See He and others (2019).

57. The amount of rare metals required for stationary power storage batteries such as those used in electric vehicle is significant (IEO, 2022); given the current technologies, phasing out fossil fuels seems quite unrealistic.

4. Conclusion

In this paper, we emphasized the importance of accounting for Nature in macroeconomic modeling by first reviewing past and present research that accounts for the material foundations of production (starting from models with nonrenewable resources to frameworks that fully develop the concept of natural capital). We then complemented this literature review by describing a novel framework. The latter extends a standard DSGE setup by embedding natural capital—defined as a variety of ecosystem goods and services essential to economic activity—alongside man-made capital.

The proposed model already features all key ingredients necessary for an informed discussion. To this end, we reviewed how natural capital and economic variables evolved towards their long-run equilibria starting from different states of the world and different assumptions regarding the evolution of natural capital: a world still rich in natural assets and a world in which these assets have been critically depleted; a world where there is no critical threshold and a world where it is possible to permanently alter the way biodiversity can regenerate over time. We also discussed some implications for economic variables and showed the role that uncertainty about some of the ecological parameters driving the stock of Nature plays in transitioning away from an equilibrium close to a tipping point.

The proposed framework opens the doors to further policy-relevant extensions, such as the study of the economic impact of greening the production structure of an economy. The latter is, we believe, an essential step forward, since without allowing the model to account for changes in the way we produce goods and relate to material consumption, any attempt at redistributing labor and human-made capital resources from the traditional sectors to the sustainable sectors in a world dominated by the former is going to prove costly in the short-run and hence without (much needed) political traction. The third part of this study offered a broad discussion of these possible extensions by emphasizing the importance of accounting for the short-run macroeconomic effects of such a transition, the tension that could materialize between local versus global environmental policies—especially when the latter are implemented without sufficient involvement of all stakeholders—, and finally the necessity to extend the framework to allow for time-dependent scenarios that can fully capture shifts in preferences, technologies, and ecological processes.

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Biodiversity vs. Climate Risk Exposures of Renewable Energy Firms

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In recent years, there has been a growing interest in understanding the intricate relationships between the economy and the health of our planet, with researchers studying both climate risks[1] and, more recently, biodiversity risks.[2] While climate and biodiversity risks interact in important ways, they are conceptually distinct. In this paper, we highlight this difference by studying risk exposures of firms in the renewable energy sector.

Renewable energy plays a key role in reducing carbon emissions and mitigating climate change, with renewable energy sources such as solar, wind, and hydropower offering lower-carbon alternatives to fossil fuels.[3] According to the International Renewable Energy Agency (IRENA), in order to meet the 2°C climate goal, the share of renewable energy in final energy consumption must increase from 19 percent in 2017 to 65 percent by 2050.[4] Regulations and policies to support

1. See Giglio and others (2021), Stroebel and Wurgler (2021), Acharya and others (2023a), Hong and others (2020).

2. See Giglio and others (2023), Karolyi and Tobin-de la Puente (2022), Garel and others (2023), Dasgupta (2021), Flammer and others (2023).

3. See Ellabban and others (2014).

4. See IRENA (2019).

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this decarbonization of the energy mix involve various efforts to raise the relative costs of fossil fuels through carbon taxes, cap-and-trade systems, and subsidies to renewable energy.[5] As a result, renewable energy companies are key beneficiaries of a tightening of climate policies and regulations: they should benefit from realizations of climate transition risks.

However, while renewable energy companies play a key role in mitigating climate change, renewable energy projects such as wind and solar farms can have negative impacts on ecosystems and biodiversity. As reviewed in Gasparatos and others (2017), the development and expansion of renewable energy infrastructure can contribute to the four key drivers of ecosystem change and biodiversity loss. First, habitat loss or alteration can occur when renewable energy projects require the conversion of natural areas into energy production sites. This can result in the disruption or displacement of native species and the destruction of critical habitats. Second, the construction and operation of renewable energy facilities can generate pollution, such as noise, light, and electromagnetic interference, which can disrupt the behavior, breeding patterns, and movement of wildlife. Third, an overexploitation of natural resources such as water or biomass can occur in the production of bioenergy or hydropower, potentially causing the depletion or degradation of ecosystems. Fourth, the introduction of invasive species can arise through the transportation and installation of renewable energy infrastructures. Consistent with this discussion, we study the risk disclosures in firms' 10-K statements and find that renewable energy firms report to be negatively affected by policies to protect nature and biodiversity: renewable energy companies should thus suffer from realizations of biodiversity transition risks.

To formally explore the risk exposures of renewable energy companies, we compare their climate and biodiversity transition risk profiles to those of otherwise-similar nonrenewable energy companies. To do so, we combine firm-level climate transition risk exposures from Sautner and others (2023) with firm-level measures of biodiversity risk exposures from Giglio and others (2023). We find that, on average, renewable-energy-related firms exhibit higher biodiversity risk exposures and lower climate transition risk exposures than nonrenewable energy firms.

We also assess the stock price response of renewable energy firms upon news about climate and biodiversity risk realizations. To do so, we form equity portfolios consisting of renewable energy companies

5. See Olabi and Abdelkareem (2022).

and test the correlation between the portfolio returns and innovations in indices measuring aggregate news about realizations of climate and biodiversity risks. We find that the correlations between the renewable energy portfolios and climate news indices are generally positive. This suggests that renewable energy firms tend to benefit from negative news or increased discussion related to climate change. Conversely, when assessing the co-movement with biodiversity news indices, we find negative correlations. This implies that renewable energy portfolios underperform upon the realization of biodiversity-related risks.

Overall, our analysis suggests that it is important to carefully consider the potential conflict between a large-scale expansion of renewable energy production and the protection of nature and biodiversity when promoting various climate policy options.[6] From an investors' perspective, our findings highlight that projects aimed at hedging portfolios against climate transition risk realizations may actually expose that investor to realizations of biodiversity transition risks.[7]

1. Biodiversity Risk and Renewable Energy Firms

According to a recent report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, five direct drivers of change in nature have accounted for more than 90 percent of nature loss in the past 50 years.[8] These drivers are land-use and sea-use alteration, pollution, invasive alien species, exploitation and utilization of natural resources, and climate change. Table 2, which is adapted from Gasparatos and others (2017), summarizes how renewable energy projects have a potential impact on biodiversity through several of these channels. Rehbein and others (2020) provide further discussions on these issues. In what follows, we summarize some of these mechanisms and explore the 10-K statements of renewable energy companies to understand the extent to which these effects on biodiversity expose renewable energy firms to biodiversity transition risks.[9]

6. See also a related discussion in Jackson (2011).
7. See also Giglio and others (2023).
8. See Brondizio and others (2019).
9. A 10-K statement is a comprehensive annual report filed by publicly listed companies with the U.S. Securities and Exchange Commission (SEC). It includes financial metrics as well as a discussion of risk factors. We collect firms' 10-K statements from 2001 to 2020 through the SEC's EDGAR database.

1.1 Land-use and Sea-use Change

Renewable energy companies' 10-K statements frequently describe a variety of mechanisms through which changes in land- and sea-use patterns from the construction of renewable energy projects and associated transmission networks can have negative effects on nature and biodiversity.

First, projects such as wind farms or solar power installations can directly cause the injury and death of various species. For example, wind turbines pose a risk for birds colliding with rotating turbine blades, and solar power plants with reflective surfaces have caused birds to be burned when flying over the plant. Similarly, turbine blades in hydropower installations can injure and kill fish. Second, the construction of renewable energy facilities and transmission lines can lead to habitat fragmentation and the disruption of the natural movement of wildlife. For example, large-scale solar installations can result in habitat fragmentation for bats,[10] and wind farms can fragment habitats used by birds for nesting and foraging; they might also alter birds' flight patterns, potentially disrupting bird populations and leading to changes in species composition.[11] In offshore environments, the installation of wind turbines and associated infrastructure can disrupt the movement of fish, marine mammals, and invertebrates.[12] Hydropower projects such as large dams can alter the natural flow of rivers and create barriers to fish migration.[13]

Examples of firms in the renewable energy sector describing such impacts on biodiversity, as well as the associated regulatory transition risk exposures, include:

> Our projects are also required to comply with the Migratory Bird Treaty Act (the "MBTA") and the Bald and Golden Eagle Protection Act (the "BGEPA"). Because the operation of solar energy projects could result in harm to endangered species or their habitats or could result in injury or fatalities to protected birds, federal and state agencies may require ongoing monitoring, mitigation activities, or financial compensation as a condition to issuing a permit for a project. [8point3 Energy Partners, LP, 2017 10-K statement]
>
> In particular, the Company's U.S. facilities are subject to the CWA [Clean Water Act] Section 316(b) rule issued by the EPA

10. See Tinsley and others (2023).
11. See Masden and others (2009).
12. See Riefolo and others (2016).
13. See Nieminen and others (2017).

[Environmental Protection Agency] that seeks to protect fish and other aquatic organisms by requiring existing steam electric generating facilities to utilize the BTA [Best Technology Available] for cooling water intake structures.[. . .] These standards require certain subject facilities to choose among seven BTA options to reduce fish impingement. [The AES Corporation, 2019 10-K statement]

In addition, laws relating to the protection of migratory birds and other wildlife could impact the development and operation of transmission lines and wind projects. [Portland General Electric Company, 2016 10-K statement]

Protection of the habitat of endangered and threatened species makes it difficult and more costly to perform some of PacifiCorp's core activities, including the siting, construction, and operation of new and existing transmission and distribution facilities, as well as thermal, hydroelectric, and wind generation plants. In addition, issues affecting endangered species can impact the relicensing of existing hydroelectric generating projects. This can generally raise the price PacifiCorp pays to purchase wholesale electricity from hydroelectric facilities owned by others, as well as reduce the generating output and operational flexibility, and potentially increase the costs of operation, of PacifiCorp's own hydroelectric resources. [PacifiCorp, 2005 10-K statement]

The habitat conservation plans (HCPs) received the support of the resource agencies, have been adopted by FERC [Federal Energy Regulatory Commission], and generally obligate the PUDs [Public Utility Districts] to achieve certain levels of passage efficiency for downstream migrants at their hydroelectric facilities and to fund certain habitat conservation measures. [Puget Energy, Inc., 2005 10-K statement]

NEP is subject to numerous environmental regulations and guidelines related to threatened and endangered species and/or their habitats, as well as avian and bat species, for the ongoing operations of its facilities. [. . .] In addition to regulations, voluntary wind turbine siting guidelines established by the U.S. Fish and Wildlife Service set forth siting, monitoring, and coordination protocols that are designed to support wind development in the U.S. while also protecting both birds and bats and/or their habitats. [. . .] Complying with these environmental regulations and adhering to the provisions set forth in the voluntary wind turbine siting guidelines could result in additional costs or reduced revenues at existing or new wind and solar facilities and transmission and distribution facilities at NEP and, in the case of environmental laws and regulations, failure to comply could result in fines, penalties, criminal sanctions or injunctions. [NextEra Energy Partners, LP, 2019 10-K statement]

> On November 22, 2013, Duke Energy entered into a settlement with the U.S. Department of Justice (DOJ) related to the incidental deaths of golden eagles and other migratory birds resulting from turbine collisions at four wind farms in Wyoming. Terms of the agreement include two misdemeanor violations of the Migratory Bird Treaty Act, payment of $1 million in fines and restitution, five years' probation, and implementation of a migratory bird compliance plan. The agreement includes a ten-year non-prosecution agreement for future incidental deaths at four facilities. Duke Energy undertakes adaptive management practices designed to avoid and minimize additional avian impacts. [Duke Energy Corporation, 2013 10-K statement]
>
> For example, the DOJ has alleged that certain NEER [NextEra Energy Resources] subsidiaries have violated the Migratory Bird Treaty Act (MBTA) and/or the Bald and Golden Eagle Protection Act (BGEPA) as a result of accidental collisions of eagles into wind turbines at the NEER subsidiaries' wind facilities without subsidiaries having permits under BGEPA for those activities. If NEER is unsuccessful in reaching a satisfactory settlement of this issue with the DOJ or if additional eagles perish in collisions with wind turbines at NEER's facilities without NEER having obtained permits for those activities, NEER or its subsidiaries may face criminal prosecution under these laws. [NextEra Energy, Inc., 2021 10-K statement]

1.2 Pollution

In addition to land-use and sea-use changes, renewable energy firms can have a negative impact on nature and biodiversity through causing pollution. For example, in the case of solar energy, the use of dust suppressants and herbicides to maximize sun access to solar panels can harm the surrounding ecosystems. Similarly, hydropower projects can contribute to pollution through changes in sediment loading and nutrient cycles. Geothermal energy projects can also result in pollution through the emission of hydrogen sulfide and boric acid.

Renewable energy firms are therefore generally required to comply with environmental laws and regulations to mitigate the impact of pollution on nature and biodiversity. Firms regularly mention these regulations as sources of biodiversity transition risks.

> Our geothermal operations involve significant quantities of brine (substantially, all of which we reinject into the subsurface) and scale, both of which can contain materials (such as arsenic, antimony, lead,

> and naturally occurring radioactive materials) in concentrations that exceed regulatory limits used to define hazardous waste. [Ormat Technologies, Inc., 2019 10-K statement]
>
> Our businesses are subject to environmental laws and regulations, including, but not limited to, extensive federal, state, and local environmental statutes, rules, and regulations relating to [. . .] natural resources and health and safety (including, but not limited to, electric and magnetic fields from power lines and substations, and ice throw, shadow flicker and noise related to wind turbines) that could, among other things, prevent or delay the development of power generation, [. . .] require additional pollution control equipment, and otherwise increase costs, increase capital expenditures and limit or eliminate certain operations. [Avangrid, Inc., 2016 10-K statement]
>
> EPA published the final national chronic aquatic life criterion for the pollutant Selenium in fresh water. NPDES permits may be updated to include Selenium water quality-based effluent limits based on a site-specific evaluation process which includes determining if there is a reasonable potential to exceed the revised final Selenium water quality standards for the specific receiving water body utilizing actual and/or project discharge information for the generating facilities. [The AES Corporation, 2019 10-K statement]

1.3 Invasive Species

In biomass energy production, the use of certain feedstocks can pose a risk of introducing invasive species. These feedstocks can propagate quickly, overpowering native vegetation and causing disturbances within local ecosystems. Consequently, regulations are in place to ensure bioenergy firms adhere to taking measures to prevent the introduction and proliferation of invasive species, and a tightening of these regulations exposes affected firms to biodiversity transition risks.

> Under the 2007 Energy Independence and Security Act, the EPA is required to produce a study every three years of the environmental impacts associated with current and future biofuel production and use, including effects on air and water quality, soil quality and conservation, water availability, energy recovery from secondary materials, ecosystem health and biodiversity, invasive species, and international impacts. [Renewable Energy Group, 2012 10-K statement]

2. Comparing Biodiversity and Climate Risk Exposures

After documenting that renewable energy firms frequently disclose substantial exposures to biodiversity transition risks, we next quantify these biodiversity risk exposures more formally and compare them across renewable and nonrenewable energy companies. We contrast our findings with the variation in climate risk exposures across the same set of firms.

2.1 Measuring Risk Exposures

The systematic measurement of firms' biodiversity transition risk remains in its early stages. Here we explore the 10K-Biodiversity-Regulation Score proposed by Giglio and others (2023) and available at www.biodiversityrisk.org. This binary variable takes a value of one if a company's 10-K statement in a given year includes at least two sentences related to biodiversity risk and one sentence related to regulatory biodiversity risk. A higher value indicates a higher biodiversity regulatory risk exposure. To measure firms' climate transition risk exposures, we use data from Sautner and others (2023). Specifically, we consider the and scores that count the frequency with which bigrams that capture regulatory climate risks are mentioned together with positive or negative tone words in one sentence in the earning call transcripts. A lower value in "$RGSentiment^{Pos}$" and a higher value in "$RGSentiment^{Neg}$" signify a higher climate transition risk exposure, suggesting that a firm would lose upon climate risk realizations.

2.2 Identifying "Renewable Energy Firms"

Transition risks affecting the production of renewable energy not only influence firms in the utilities sector that produce renewable energy directly. Instead, these risks could also affect, for example, the suppliers of such firms. For example, regulations to protect the environment do not just hurt utilities that produce solar energy but also suppliers of solar panels in the semiconductor sector. To determine which firms are affected by shocks to the production of renewable energy, we exploit the holdings of renewable energy ETFs such as

Invesco Global Clean Energy ETF (PBD), iShares Global Clean Energy ETF (ICLN), VanEck Low Carbon Energy ETF (SMOG), SPDR S&P Kensho Clean Power ETF (CNRG), Invesco Solar ETF (TAN), and First Trust Global Wind Energy ETF (FAN). We obtain portfolio holdings of these ETFs from Bloomberg from March 2023, focusing on North American common stocks.

2.3 Comparing Risk Exposures

To examine the average biodiversity and climate risk exposures of renewable energy firms in comparison to nonrenewable energy firms, we use the following cross-sectional specification:

$$Risk\ Exposure_i = \beta \cdot 1\,(Renewable)_i + Controls_i + \in_i \tag{1}$$

where $Risk\ Exposure_i$, is one of the 10K-Biodiversity-Regulation Score, $RGSentiment^{Pos}$, or $RGSentiment^{Neg}$ of firm i. $1(Renewable)_i$ is an indicator for a renewable energy firm, set equal to one if it is held by at least one of the renewable energy ETFs. Table 1 shows the result. Columns (2), (4), and (6) include firm controls for size and book-to-market (B/M). Size is the logarithm of firm i's market capitalization, and B/M is firm i's book value divided by its market capitalization, winsorized at the 2.5 percent level. All measures are averaged over a five-year period between 2018 and 2022. The sample includes all firms for which both the Giglio and others (2023) and the Sautner and others (2023) measures are available.

We find that β is positive and significant for biodiversity regulatory risk exposure and positive mention of climate regulation bigrams, while it is negative and significant for negative mention of climate regulation bigrams. This finding suggests that renewable energy firms are substantially more exposed to biodiversity regulatory risk and less exposed to climate regulatory risk compared to nonrenewable energy firms. The positive coefficient on highlights that renewable energy firms are not only less exposed by regulatory climate interventions but also more likely to be beneficiaries of these regulations.

Table 1. Renewable Energy Firms and Risk Exposure

	Biodiversity Regulation Risk		*RGSentiment^{Pos}*		*RGSentiment^{Neg}*	
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*
1(*Renewable*)	0.026**	0.029**	0.017***	0.016***	-0.004***	-0.004***
	(0.012)	(0.012)	(0.002)	(0.002)	(0.001)	(0.001)
LogSize		0.001		0.001***		-0.000**
		(0.001)		(0.000)		(0.000)
B/M		0.044***		0.003***		-0.001***
		(0.006)		(0.001)		(0.000)
Observations	2,368	2,368	2,368	2,368	2,368	2,368

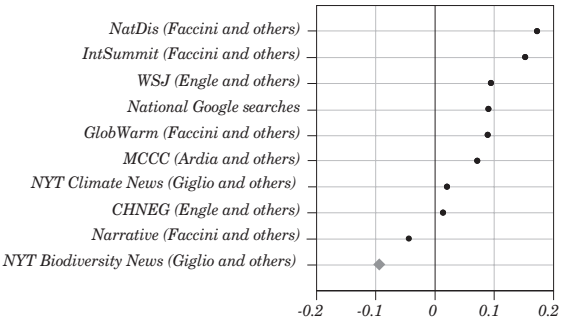
Source: Authors' calculations.
Notes: This table shows results from regression 1. *Biodiversity Regulation Risk* takes a value of one if a company's 10-K statement in a given year includes at least two sentences related to biodiversity risk and one sentence related to regulatory biodiversity risk. It is provided by Giglio and others (2023). *RGSentiment^{Pos}* is the relative frequency with which bigrams that capture regulatory shocks related to climate change are mentioned together with positive tone words in the transcripts of earnings conference calls. *RGSentiment^{Neg}* measures the relative frequency with which bigrams that capture regulatory shocks related to climate change are mentioned together with negative tone words in the transcripts of earnings conference calls. Both climate risk exposure measures are provided by Sautner and others (2023). We multiply the *RGSentiment^{Pos}* and *RGSentiment^{Neg}* by 100. The sample includes all firms for which both biodiversity and climate risk exposure measures are available. 1(*Renewable*) is an indicator for a renewable energy firm, set equal to one if it is held by at least one of the renewable energy ETFs described in the main text. *LogSize* is the logarithm of firm's market capitalization. *B/M* is firm's book value divided by its market capitalization, winsorized at the 2.5 percent level. For all measures, we average over 2018 to 2022. Significance levels: ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

2.4 Hedging Climate and Biodiversity Risks

We also investigate the covariance of renewable energy firms' stock returns with news about climate and biodiversity risk realizations.

We begin by forming portfolios of the renewable energy firms identified as described above. Specifically, we construct a renewable energy portfolio that goes equally long for all the renewable energy firms. To capture aggregate biodiversity risk realizations, we study AR(1) innovations of the NYT-Biodiversity News Index developed by Giglio and others (2023). To capture climate risk realization, we work with AR(1) innovations in several climate risk news series proposed by Ardia and others (2020), Engle and others (2020), and Faccini and others (2021).

Figure 1. Climate and Biodiversity Hedge Performance of Renewable Energy Portfolio



Sources: As indicated.
Notes: Dot plot of monthly return correlations for the renewable energy portfolio with AR(1) innovations of various indices using data from 2010 to 2020. The dots in the top nine rows show the correlations with climate indices by Ardia and others (2020), Engle and others (2020), Giglio and others (2023), and Faccini and others (2021), and a national Google search index. See detailed discussion of these indices in Alekseev and others (2022). The diamond in the bottom row shows the correlation with the NYT-Biodiversity-News index developed by Giglio and others (2023). Each dot represents one correlation coefficient.

Figure 1 presents correlations at the monthly level between the returns of our renewable energy portfolio and various innovations of biodiversity and climate risk indices. The correlations between 2010 to 2020 indicate that renewable energy-related firms generally exhibit a positive correlation with climate news while demonstrating a negative correlation with biodiversity news. In other words, while these firms tend to gain from climate risk realizations, they suffer from biodiversity risk realizations, consistent with the direction of their risk exposures established above.

3. Concluding Thoughts

Renewable energy firms are instrumental in combating climate change through their provision of clean and sustainable energy sources.[14] Yet, it is important to recognize that these firms' activities can simultaneously contribute to nature and biodiversity loss. As a result, they are substantially exposed to biodiversity transition risk. As the world transitions to a low-carbon economy, it therefore becomes crucial for researchers and regulators to separately manage

14. See Acharya and others (2023b).

biodiversity and climate risks, potentially necessitating a reevaluation of existing climate-related policies and regulations in light of emerging biodiversity risks. To further advance the management of biodiversity risks, regulators should thus focus both on improving measurement and disclosure of these risks and on stress testing the financial system to realizations of these risks.

3.1 Measures and Disclosures

Unlike climate risk, which can be quantified to some extent through metrics such as carbon emissions, biodiversity risk poses unique challenges in measurement, assessment, and disclosure.

Recent research has proposed various methodologies to measure and assess biodiversity risk. These approaches include analyzing 10-K statements, conducting surveys, and utilizing information from biodiversity-themed ETFs holding.[15] Additionally, third-party measures such as the Corporate Biodiversity Footprint have been applied to provide insights into companies' impacts on biodiversity,[16] though the construction of measures provided by commercial vendors is often opaque. In terms of disclosure, efforts have been made to enhance transparency and reporting on biodiversity-related issues. One notable initiative is the Taskforce on Nature-related Financial Disclosures (2022), which aims to provide a framework for companies and financial institutions to disclose and manage their nature-related risks and opportunities. Additionally, organizations such as the Carbon Disclosure Project (CDP) have begun to include biodiversity-related information in their reporting frameworks.

While these initiatives represent important steps towards better disclosures of biodiversity risks, regulators should further focus on enabling firms to measure and disclose their biodiversity risks.

3.2 Stress Test

The recognition of potential risks posed by climate change to the economy has spurred central banks and regulatory authorities worldwide to assess and manage climate-related risks through climate stress tests.[17] The risks associated with biodiversity loss, although

15. See Giglio and others (2023).
16. See Garel and others (2023).
17. See Acharya and others (2023a).

increasingly acknowledged, have received less attention in comparison. Recognizing the need to broaden the scope of environmental risks, the Network for Greening the Financial System[18] acknowledges that environmental risks extend beyond climate change, prompting institutions such as De Nederlandsche Bank[19] and Banque de France[20] to incorporate biodiversity risk into their stress testing systems. As our understanding of the potential materiality of biodiversity risks evolves, regulators and central banks may consider the inclusion of such risks in their stress-testing frameworks.

Table 2. Impacts of Renewable Energy Companies on Biodiversity

	Habitat Loss & Change	*Direct Mortality*	*Pollution*	*Invasive Species*
Solar energy	Land occupation by infrastructure; Habitat fragmentation by infrastructure and land preparation.	Bird collisions and solar ray burning; Attraction and disorientation of insects.	Dust suppressants and herbicides.	
Wind power	Land occupation by infrastructure; Downdraught generated by the spinning blades; migratory routes disruptions of birds and bats.	Birds and bats collisions with wind generators		
Hydropower	Upstream flooding and habitat fragmentation by plants and dams; Modification of water flow regimes; Obstacles to fish migration.	Fish passage into turbines.	Eutrophication caused by changes in sediment loading and nutrient cycles.	

18. See NGFS (2021).
19. See De Nederlandsche Bank (2020).
20. See Banque de France (2021).

Table 2. Impacts of Renewable Energy Companies on Biodiversity (continued)

	Habitat Loss & Change	*Direct Mortality*	*Pollution*	*Invasive Species*
Biomass energy and biofuels	Land use change resulting from the expansion of biomass feedstock and feedstock cultivation; changing size and shape of plants; alteration of landscape features; soil loss.		Eutrophication, acidification, and toxicity resulting from greenhouse gases (GHGs) and atmospheric/ water pollutants generated through bioenergy production	Some biomass energy feedstocks might be invasive
Geothermal energy	Land occupation by infrastructure; changes caused by site clearing, road construction, well drilling, and seismic surveys.		Emission of toxic pollutants; elevated arsenic concentration in water and soil; noise and heat pollution	
Marine energy (tidal, wave, thermal, offshore wind)	Land occupation by infrastructure; operation of ocean energy devices that can disrupt bird and aquatic species' movement and feeding activity; alteration of the characteristics of the marine environment.	Fish entrapment caused by tidal barrages; fish mortality due to temperature shocks from upwelled cold water; bird collisions with offshore wind farms.	Chemical, noise, and electromagnetic pollution.	

Source: Authors' research.
Notes: Adapted from Table 3 in Gasparatos and others (2017), which also lists sources documenting evidence for the various impacts.

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The Social Cost of Carbon—What's New and Next?

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As described by Fridligstein and others,[1] atmospheric concentrations of CO_2 have risen from 278 parts per million (ppm) in 1750 to 419.3 ppm in 2023. While pre-industrial revolution growth in concentrations was largely due to land use changes and deforestation, the source of emissions rapidly shifted towards the combustion of fossil fuels, with a total of 490 +/- 25 gigatons of carbon being emitted between 1850 and 2023. Roughly 46 percent of cumulative emissions stemmed from coal, 35 percent from burning of oil, and 15 percent from burning of natural gas. In 1850, the United Kingdom was responsible for 62 percent of emissions, yet today China (31%), the United States (13%), India (8%), and the EU-27 countries (7%) are responsible for roughly 60 percent of total emissions. Unmitigated growth in the combustion of fossil fuel will continue to drive up atmospheric concentrations leading to increased atmospheric forcing, which will translate into changing weather patterns including, but not limited to, higher temperatures in summer and winter, changed precipitation patterns, storm intensities, and area burned by wildfires.[2]

This paper is a writeup of the keynote delivered at the XXVI Annual Conference of the Central Bank of Chile, "Implications of Climate Change and Ecosystem Services Degradation for Macroeconomic and Financial Stability" on November 28, 2023. All errors are the author's.

1. See Friedlingstein and others (2025).
2. See IPCC (2023).

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Emissions of greenhouse gases (GHG) present one of the more complex cases of a global externality, as most GHGs are long-lived and mix fairly uniformly around the globe. Hence the damages from a ton of, for example, CO_2 emitted accrue to humans and ecosystems globally —regardless of the source or location of emissions— and to possibly dozens of future generations due to the stock-pollutant-like nature of CO_2. The issue is further complicated by the fact that the ambient environment is a key input to virtually all economic sectors—both market (e.g., agriculture, energy consumption, productivity) and nonmarket (ecosystem services, mortality, biodiversity).

Basic economic theory going back to Pigou (1920) suggests that the first-best solution is a per-unit carbon tax set at the marginal external damage. To set a remotely optimal carbon tax, one must know what the external damage of different GHGs along their emissions paths is. The question arises of how to calculate the marginal damage of a single ton of GHGs at a given point in time.

In 2024, roughly 24 percent of global GHG emissions were covered by a form of carbon pricing. Six percent of emissions are covered by a carbon tax and the remaining 18 percent by a tradeable permit system. Prices charged per ton of CO_2 range from USD 0.61 (Indonesia Emissions Trading System) to USD 167 (Uruguay's Carbon Tax). Permits in the larger carbon markets were trading at about USD 61 (EU ETS), USD 39 (California ETS), USD 18 (Regional Greenhouse Gas Initiative—RGGI), and USD 14 (China National ETS).[3]

The Social Cost of Carbon (SCC) under certain assumptions provides an estimate of the external damages from one ton of CO_2 emitted at a point in time. The SCC can hence not only provide guidance as to how to set an optimal emissions tax but also be used in benefit-cost analysis to evaluate proposed and existing policies. Calculating this "most important number few people have heard of" has an important history in academia and provides a premier case study of how an academic exercise turned into a tool that has evaluated trillions of dollars in benefits in benefit-cost analyses across the globe.

In what follows, I briefly describe its evolution and provide an overview of key next steps in this important and active research agenda.

3. See World Bank (2025).

1. Historical Evolution of the Social Cost of Carbon

The impact of climate change on economic outcomes has a long history in the field. One of the early examples of such work is Huntington (1917), who argues that long-term climate variability and soil degradation were significant contributors to the decline of the Roman civilization. He reviews historical, archaeological, and ecological evidence suggesting that shifts in rainfall patterns and increasing aridity led to lower agricultural productivity, which in turn triggered social and political instability. Yet quantifying the economic damages of a single ton of CO_2 in an academically rigorous way did not start until the 1980s. William Nordhaus' (1982) paper in the *American Economic Review* started off a literature that accelerated in the 1990s.[4] Bill Cline's book (1992) is often cited as one of the seminal works that outlined the issue and, most importantly, characterized what one would need to understand in order to credibly calculate economic damages. There are a number of great reviews of the history of SCC, which are worth consulting for those interested.[5]

William D. Nordhaus is widely recognized for advancing the concept of the social cost of carbon, particularly through the development of his Dynamic Integrated Climate-Economy (DICE) model beginning in the 1990s.[6] By integrating economic theory with climate science, Nordhaus provided a framework for quantifying the economic damages associated with carbon emissions, significantly shaping the way policymakers and economists approach climate-related externalities. While the conceptual framework is clearly key to answering the question of how a changing climate affects current and future economic welfare, calculating that number poses a massive challenge that requires drawing on tools, methods, and insights from across the field of economics and beyond; for example, climate science. In the early days, three approaches emerged. Nordhaus (1994) simply asked experts what they thought economic damages of climate change were going to be. In his 1992 DICE and 1996 Regional Integrated Climate-Economy (RICE) work, he and others in the literature would rely on the "enumerative methods".[7] The enumerative approach

4. For example, Ayres and Walter (1991), Nordhaus (1991), Haraden (1992), Peck and Teisberg (1993), Reilly and Richards (1993), Fankhauser (1994), Smith (1996), Titus (1992).

5. For example, Tol (2011), and Chapter 5 in National Research Council (2010).

6. See Nordhaus (1992, 1994).

7. See Tol (2011).

proceeds by assembling estimates of the physical impacts of climate change one at a time, typically drawn from natural science research based on laboratory experiments, climate models, or impact models. Each identified effect is then assigned a monetary value, and the resulting figures are aggregated to produce an overall estimate. A third approach, known as the *statistical approach*,[8] relies on directly estimating welfare impacts by exploiting observed spatial variation in climate within a single area. By examining how land prices, incomes, and expenditures differ across regions, this method infers the economic effects of climate differences.

Prior to 2008, the social cost of carbon literature was largely academic, and there was not one single number that was used in the required regulatory impact analyses (RIA) underlying federal rulemaking. A ruling by the Ninth Circuit Court of Appeals pushed back on a proposed fuel efficiency rule by the Department of Transportation, suggesting that failure to place a monetary value on foregone damages from avoided climate change due to more efficient vehicles was "arbitrary and capricious". In response, the Obama administration in 2009 convened an Interagency Working Group (IWG) made up of representatives from all relevant agencies[9] to come up with a scientifically defensible social cost of carbon. The IWG chose three prominent integrated assessment models (IAM) available at the time to calculate an SCC: the DICE,[10] the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND),[11] and the Policy Analysis of the Greenhouse Effect (PAGE).[12] An IAM links GHG emissions to atmospheric concentrations, projects resulting in changes in temperature and climate, estimates of physical impacts (like sea level rise or crop loss), translates those into economic damages, and discounts future harms to present value. The three chosen IAMs differ in structure and assumptions, but all aim to provide a coherent estimate of the SCC. It is noteworthy that two of the models were open-source (DICE, FUND) and one was not (PAGE).

8. See Nordhaus and others (1994); Mendelsohn and others (2000 a,b).

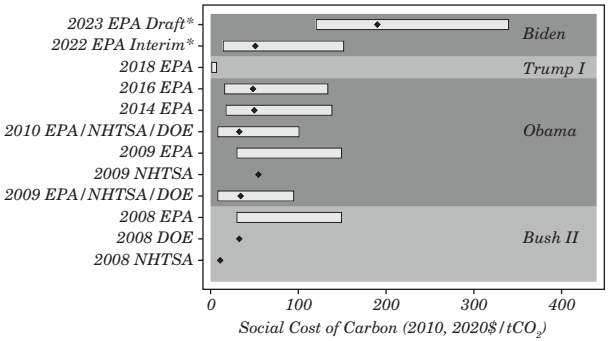
9. Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Energy, Department of Transportation, Environmental Protection Agency, National Economic Council, Office of Energy and Climate Change, Office of Management and Budget, Office of Science and Technology Policy, Department of the Treasury.

10. Nordhaus (1992).

11. Tol (1996); Anthoff and Tol (2014).

12. Hope (1993).

Figure 1. Historical Values of the SCC by the U.S. Federal Government



Source: As indicated.
Notes: Ranges indicate high and low values reported. The diamond indicates a central value reported. All values are for the 2010 social cost of carbon, except for the * values, which are for 2020, as the report does not list a 2010 number.

The Interagency Working Group largely adopted the default assumptions chosen by the original developers of the IAMs, including parameter values and functional forms.[13] However, two notable departures stand out: the IWG applied a unified probability distribution for the equilibrium climate sensitivity (ECS) across all three models and relied on a standardized set of five socioeconomic and emissions scenarios to project future conditions. Additionally, the present value of projected damages was calculated using three fixed discount rates applied consistently across the models. In the technical support document, the IWG presented the distribution of the SCC for different years of emission and discount rates, weighting each IAM equally.

There were numerous updates to the SCC during the two Obama administrations, ultimately settling at an SCC of USD 42/ton emitted in 2020.[14] The Obama administration asked the National Academies of Sciences, Engineering, and Medicine (NASEM) to review their methodology to calculate the SCC, and an expert panel was convened. This panel delivered its finding weeks before the 2017 inauguration of President Donald Trump, whose one of his earliest executive actions disbanded the IWG and reset the SCC to USD 1–7, by restricting damages to domestic damages only and increasing

13. See IWG (2010).
14. See IWG (2016).

the discount rate. Four years later, President Biden reconvened the IWG and reinstated the SCC to USD 51/ton, which was a simple adjustment for inflation of the Obama SCC. He also charged the IWG with implementing the changes suggested by the National Academies. Figure 1 below shows the historical values of the SCC used by the U.S. Federal Government—a number that has been adopted by numerous governments across the world.

2. The Current State of Affairs

After the announcement of the dissolution of the IWG in 2017, academics took up the challenge to address the short-run and some of the long-run suggestions made by the National Academies (2017). Two teams formed separate but connected efforts to improve the SCC—the Climate Impact Lab (CIL) (University of California at Berkeley, University of Chicago, Rutgers University, and Rhodium) and Resources for the Future (RFF). The progress resulted in modelling that ultimately led to the updated SCC of USD 190/tCO_2.[15] Here I summarize some of the significant changes in modelling of the different "modules" (socioeconomic scenarios, climate, damage functions, and discounting) using the recent Greenhouse Gas Impact Value Estimator (GIVE)[16] model and the Data-Driven Spatial Climate Impact Model (DSCIM)[17] and show the impacts of some of the modelling choices on the distribution of the SCC. Rennert and others (2022) and the Environmental Protection Agency (EPA) (2023) provide a significantly more detailed discussion of the modelling innovations, which I summarize below.

2.1 Socioeconomic Module

Resources for the Future developed a set of long-run probabilistic socioeconomic pathways to meet the specific requirements of estimating the SCC. These include the need for: (i) a 300-year time horizon to capture most discounted climate damages; (ii) regionally disaggregated GDP and population data; (iii) accounting for uncertainty in future technology and policy, including anticipated mitigation efforts; and (iv) modeling the interdependence of population, economic growth, and emissions.

15. See EPA (2023).
16. See RFF (2025).
17. See CIL (2022).

These scenarios address limitations in the earlier pathways used by the IWG, which drew on five deterministic pathways extending to 2100. Those scenarios were criticized for their narrow uncertainty range and limited representation of global scenario literature. In contrast, the new pathways explicitly characterize uncertainty using a mix of statistical and expert-driven methods. Country-level population projections through 2300 extend the United Nation's probabilistic framework, with expert review from leading demographers. For GDP per capita, the study employs a multifactor Bayesian dynamic model centered on a global frontier, calibrated using expert elicitation data from the RFF Economic Growth Survey.

Unlike the previous pathways, which were scenario-based and lacked explicit probability distributions, the new scenarios offer fully probabilistic projections that better reflect deep long-term uncertainty. Wide ranges in the scenarios underscore the limitations of the previous scenarios beyond 2100, which provided a false sense of confidence.

In addition, the new model uses a survey to construct probabilistic, multi-century emissions trajectories not only for CO_2, but also for CH_4 and N_2O. These incorporate expert assessments of technological change, mitigation policies, carbon sinks, and the interaction between economic growth and emissions. This joint modeling of socioeconomic and emissions uncertainty provides a more robust foundation for estimating the SCC and is publicly available for uses beyond the modeling of the SCC.

2.2 Climate Model

In the new approach, the global climate system and carbon cycle are represented using the Finite Amplitude Impulse Response (FaIR) model,[18] a reduced-complexity emissions-based climate model. FaIR incorporates state-dependent feedbacks by linking cumulative carbon uptake and background warming to the efficiency of land and ocean sinks. This enables the model to replicate key equilibrium and impulse-response behaviors observed in more complex Earth system models—capabilities absent from earlier models used in SCC estimation. FaIR is run using probabilistically sampled emissions trajectories for CO_2, CH_4, and N_2O from the scenarios discussed above. Climate response uncertainty is addressed through a 2,237-member ensemble

18. See Millar and others (2017).

of calibrated parameters developed for the IPCC's Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). In short, the new climate modeling approach addressed the significant criticisms raised by the climate scientists on the NASEM report.

Sea-level rise in GIVE is modeled using Building Blocks for Relevant Ice and Climate Knowledge (BRICK),[19] which generates probabilistic projections of regional sea-level change by combining contributions from thermal expansion, glaciers, ice sheets, and land water storage. BRICK is calibrated against observed sea-level data from 1850–2017 using a Bayesian framework, with priors informed by paleoclimate evidence and previous studies. A Markov chain-based approach enables robust propagation of uncertainty and captures tipping dynamics in the Antarctic ice sheet.

2.3 Damage Functions

Previous IAMs had employed severely outdated damage functions.[20] A desirable damage function for these models should:

- be applicable globally,
- incorporate long-run adaptation,
- carry a causal interpretation,
- be valid for 200+ years, and
- allow for heterogeneity across space, groups, and time.

The two empirically based damage modules (GIVE and DSCIM) differ in terms of the parameterization of the damage functions as well as sectoral coverage.[21] GIVE models damages for health, energy, agriculture, and coastal regions. The damage functions the RFF/GIVE team drew on are drawn from the existing literature and a reanalysis thereof in some cases. What is noteworthy in the damage function for agriculture in this model is the fact that it incorporates some general equilibrium/trade effects based on Moore and others (2017).

The DSCIM model developed by the CIL includes damages for health, energy, labor productivity, agriculture, and coastal regions. What is appealing about the DSCIM damage functions is that they are estimated by using a consistent econometric framework that uses

19. See Wong (2017).

20. See EPA (2023).

21. A more detailed discussion of the estimation of damage functions is provided in EPA (2023), Carleton and Hsiang (2016), Auffhammer (2018), and Kolstad and Moore (2020).

variation in weather to parameterize local response to weather shocks, which can vary based on income and climate. This allows one to "bend" the damage function as a future world becomes warmer and richer. To parameterize their damage functions, the CIL collected a massive dataset on subnational outcomes (e.g., mortality and agricultural yields) and weather data and used econometrically estimated damage functions to extrapolate global damages.

Literature often attaches a causal interpretation to these damage functions. This is a reasonable assumption in sample; yet, as anyone would acknowledge, whether a functional relationship parameterized on historical data is "causally valid", 275 years in the future is maybe overly optimistic. Imagine forecasting global emissions for 2025 in the year 1750—prior to the industrial revolution—even if one had the statistical insights and computational ability we do today. It is important to acknowledge the uncertainty—beyond the econometric uncertainties—inherent in these damage functions going forward. It is also important to acknowledge that the forecast error here could go in both directions, depending on whether and how we adapt to climate change.

2.4 Discounting

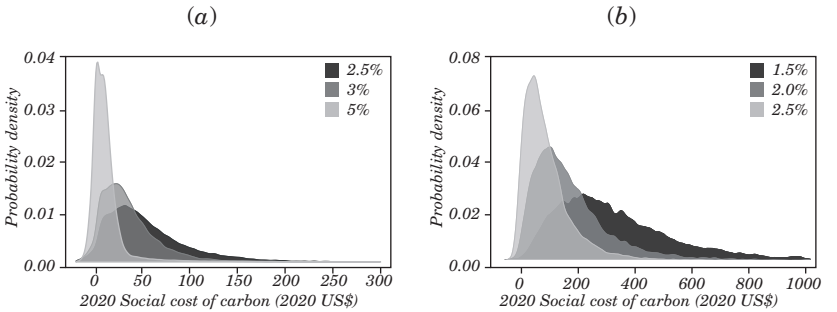
The updated approach follows the discounting framework recommended by the NASEM, summarized in Newell and others (2022). Because CO_2 remains in the atmosphere for centuries, today's emissions generate damages far into the future, which must be discounted back to the present. The new IAMs adopt a Ramsey-style discounting approach, linking discount rates to economic growth. This formulation structurally models uncertainty in future consumption growth, producing a stochastic discount factor (SDF) that reflects variability in discount rates over time. Unlike earlier U.S. government estimates that assumed a constant discount rate and no risk aversion, this method reinstates the theoretical link between growth and discounting. The calibration employed yields a near-term discount rate of 2 percent, aligning with historical real risk-free interest rates. This Ramsey-style model—despite alternatives like ambiguity aversion—remains the dominant framework for regulatory and policy analysis under uncertainty, given its ability to incorporate both risk and intertemporal substitution in valuing climate damages currently.

2.5 Impacts of Modelling Choices

Much discussion surrounds what the impacts of different modelling choices are on the significantly higher SCC after updates were implemented. Rennert and others (2022) show a comparison of the GIVE model to the DICE model under different assumptions and conclude that the choice of discount rate is the single biggest contributor to the higher SCC, followed by the updates to the damage function. Another exercise one could conduct is to compare the distributions of the SCC before and after the update, which I show in Figure 2, below. It is clear that the distributions for the updated SCC have significantly higher density in the right tail. But is this simply due to the difference in discounting? The pre-update version used discount rates of 2.5, 3, and 5 percent, while the updated version used 1.5, 2, and 2.5 percent, in addition to a different discounting approach, partly based on expert elicitation work by Drupp and others (2018).

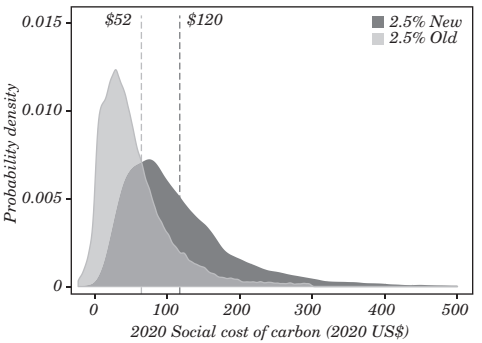
In Figure 3, I overlay the distributions for the discount rate scenarios that overlap in rate. The dashed distribution uses the constant rate 2.5 percent approach, while the solid distribution uses the Ramsey style 2.5 percent approach. One can see that there is a difference in the central tendency of USD 68/ton, which is not purely due to the choice of discounting, which is significant given the overall increase from USD 52/ton to USD 190/ton.

Figure 2. The Social Cost of Carbon Pre and Post Update



Source: Author's research.

Figure 3. SCC Pre and Post Update for the Same Discount Rate



Source: Author's research.

3. The Next Steps

The revisions of the SCC released in EPA (2023) addressed most of the short-run recommendations made by the National Academies (2017) as well as some of the longer-run recommendations. There remain, however, several aspects of how the SCC is calculated that will serve as fruitful avenues of research.

3.1 Sectoral Coverage

The most recent modelling effort covers five sectors—human mortality, agriculture, energy, coastal property, and productivity. These sectors were included due to the availability of data resources to estimate damage functions, which were thought to satisfy the criteria discussed above. The only previously used model that had meaningful sectoral resolution, the FUND model, covered many more sectors, such as forestry, water resources, vector-borne diseases, and big storms. Sectors that are not included at all are species loss, migration, air pollution, wildfires, crime & conflict, human amenity value, and morbidity, to name but a few. While with increasing data availability there are significant efforts underway to add forestry, wildfires, and migration, there is still much work to be done for additional sectors. As the National Academies report pointed out, the further one gets from goods and services traded in markets, the harder it gets to quantify welfare effects. One of the most important aspects of further

inquiry is the climate-change-induced loss of natural amenities and, more generally, natural resources. Environmental economics has a long history valuing natural resources, and efforts to link these to the social cost of carbon are in their early stages. One can, however, envision ways that the study presented at this conference by Justin Johnson and Steve Polasky could link to the SCC work, which could meaningfully enrich the next estimates of the social cost of carbon.

3.2 General Equilibrium and Spillover Effects

Many commodities are traded in global markets, and some are storable for varying time horizons. This is especially true for agriculture. As climate change shifts local weather distributions around the globe in significant ways, it will continue to be true that, while some regions might experience a negative weather shock, others might not—in the same year. The effect of a negative weather shock in one region on local and global crop prices is likely going to depend on what is happening in grain-producing regions elsewhere. A bad shock in Australian wheat might be offset by a good year in Canadian wheat, for example. Further, as has been pointed out in a massive literature in agricultural economics, the level of existing storage might also be able to smooth out local negative weather shocks' effects on global prices. The vast majority of damage functions and currently used models do not explicitly build in trade and global general equilibrium effects into the calculation of the social cost of carbon. There is, however, a burgeoning literature in international trade that explicitly models the effect of climate shocks on trade; for example, Desmet and Rossi-Hansberg (2024).

While modeling spillover effects in a trade context is part of the economics toolkit, other sectors are much more difficult to model. Specifically, it is hard to model and almost impossible to monetize the effect of migration on economic outcomes or on conflicts or other indirect effects of climate shocks on conflicts; for example, negative yield shocks that can set off local violent conflicts. While one might hope to be able to quantify some of these effects for specific local areas, it is more difficult to imagine a damage function, for example, weather and conflict, that also has monetized welfare impacts attached. The National Academies report urges regulators when it is not possible to monetize outcomes, to list them in the units the individual damage sector is reported or measured in.

3.3 Equity Weighting

As discussed above, the practice of discounting has received extensive attention in the calculation of the social cost of carbon. This practice reflects how society values current versus future costs and benefits. However, there is a similar concept that has received much less attention—the practice of income or equity weighting. It is generally well understood that the marginal value of a dollar's worth of consumption to a poor person is higher than the value of that same dollar to a rich person. Further, as Prest and others (2024) point out, climate impacts are often monetized using estimates of individuals' willingness to pay (WTP) for mitigation, but these measures are constrained by individuals' income levels, meaning that lower-income populations typically register lower WTP values. As a result, monetized damage assessments may systematically undervalue the harms faced by these groups, raising ethical and equity concerns for many observers. Equity weighting incorporates distributional weights into regulatory analysis, assigning greater marginal value to benefits and costs accruing to lower-income populations relative to higher-income groups, which addresses both concerns.[22] Equity weighting is used by the German government in its calculation of the SCC. The United Kingdom and, more recently, the United States have allowed for the use of equity weighting in benefit-cost analysis. The question is, of course, whether this makes a significant difference when calculating the SCC. Prest and others (2024) show, using the GIVE model, that incorporating equity weighting for reasonable choices of weighting parameter(s) increases the SCC by a factor of 8, which suggests that addressing this important issue has significant effects on the number ultimately used in benefit-cost analyses.

3.4 Domestic versus Global Number

There has been a small but vocal movement among certain policymakers to advocate for the use of a domestic SCC in climate policy, effectively discounting harms incurred beyond national borders. This approach was most notably institutionalized under the first Trump administration, which recalibrated the social cost of carbon to reflect only domestic damages. Yet this is fundamentally at odds with the nature of GHG emissions, which constitute a global externality—

22. See Azar and Sterner (1996); Anthoff and Hepburn (2009); Anthoff and others (2009).

damages from a marginal ton of CO_2 accrue both domestically and internationally. Achieving global efficiency in climate policy requires each country, including the United States, to employ a globally derived SCC in its regulatory analysis. If instead each nation relied solely on a domestic SCC, the aggregate abatement level would fall well below the globally optimal benchmark, resulting in inefficiently high emissions across the board.

Moreover, the SCC a country adopts has strategic implications. As Kotchen (2018) notes, all nations possess a "strategic SCC" that is different from their purely domestic SCC, reflecting the interdependent nature of global climate action. The SCC adopted by one country can influence the choices of others, creating a strategic complementarity that reinforces the case for a globally harmonized metric.

Beyond these conceptual arguments, current models are ill-suited to produce accurate domestic SCCs, especially when "domestic" is defined in terms of citizenship. For instance, the U.S. military maintains a global presence with approximately 450,000 personnel stationed overseas, whose exposure to foreign-climate impacts directly links U.S. emissions to the welfare of U.S. citizens abroad. The same applies to the estimated 9 million U.S. civilians living overseas. A domestic-only SCC would effectively assign a welfare weight of zero to all of these individuals, as the models can only calculate damages by region, not residency.

Additionally, climate change is projected to increase the frequency and severity of global conflict, potentially triggering U.S. military deployments and broader geopolitical instability. These general equilibrium effects—ranging from increased troop exposure to downstream disruptions in global supply chains for critical inputs like rare earth elements—are omitted from current SCC models. This omission further underscores the inadequacy of a domestically bounded SCC in capturing the full scope of climate damages relevant to national welfare.

3.5 Extreme Events

One of the most forceful criticisms of IAMs relates not only to their parameterization, but also to their current inability to meaningfully incorporate catastrophic climate risk.[23] Pindyck's central critique is

23. See Pindyck (2013, 2017).

both that these models are built around arbitrary assumptions that tend to focus narrowly on expected outcomes and marginal changes in global average temperature, translating those into smooth welfare losses over long time horizons. But this framing misses what should be the main concern: the risk of rare but severe tail events—climate tipping points, runaway feedback loops, or large-scale ecological collapse—that could lead to dramatic and irreversible damage to human welfare and economic systems. These are precisely the types of outcomes that economic theory tells us should dominate decision-making under uncertainty, yet current IAMs are not capable of capturing them in a rigorous fashion. Pindyck argues that this results in a false sense of analytical precision, as these models generate point estimates of the social cost of carbon that appear authoritative, but in reality, they rest on assumptions that are deeply uncertain and, in many cases, untestable. Pindyck's view is that this modeling paradigm is misleading for policy. Rather than trying to optimize emissions reductions based on these models, he argues for a risk-management approach that treats climate policy as a form of insurance.

4. Conclusions

The social cost of carbon represents a key parameter when evaluating the cost and benefits of policies that will affect the emissions of greenhouse gases going forward. Recent updates by the U.S. Environmental Protection Agency with significant support from academics resulted in an increase of the SCC from USD 52/ton to USD 190/ton. This represents one of the most successful transfers of academic research into the policymaking process to date. However, much work remains to be done. Sectoral coverage is missing important sectors such as forests, biodiversity, conflict, migration, and morbidity, to name but a few. Further, the treatment of extreme events is limited and mostly does not incorporate truly extreme events, which may dominate the marginal changes currently modeled. A most promising active research agenda is building around extending the incorporation of general equilibrium and trade effects into the SCC. Further opportunities for interdisciplinary collaboration present themselves in the discussion around equity weighting, which has linkages to philosophy. Further, a deeper discussion around the legal aspects of using a domestic social cost of carbon is warranted, as the economics are clear. While the SCC is often seen as a number that is used solely in benefit-cost analysis, it is used in the private sector and by financial

institutions as a measure of carbon damages when fully evaluating companies and "green" investment opportunities, extending its reach beyond ministries of energy and the environment.

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The Possibility and Plausibility of Large Macroeconomic Impacts from Climate Change

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Does climate change represent a serious or even catastrophic threat to future lives and livelihoods, or is it more likely to be a relatively modest annoyance that most of the world will be able to straightforwardly deal with? Proponents of both views are commonly found in both academic literature and broader popular and policy debates. Surveys of academic experts have found very wide variation in expectations of potential economic damage from future climate change, with some expecting negligible economic impacts and others foreseeing substantial possible declines in future economic output from a warming climate.[1] Early economic analysis using integrated assessment models suggested that climate change might reduce economic output by only a few percentage points by 2100[2]—or roughly one to two years of economic growth, hardly an economic catastrophe. However, more recent microeconometric and sector-specific work suggests the possibility of much more substantial economic damage

1. See Pindyck (2019).
2. See Revesz and others (2014).

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when impacts are summed across sectors.[3] Perhaps consistent with these findings, a growing body of empirical work using national and subnational macroeconomic data also suggests the possibility of much larger aggregate future damages from climate change.[4] Reconciling these disagreements on the potential magnitude of the effects of climate change on the economy and related outcomes is important for scaling mitigation ambition and anticipating adaptation needs.

Here we revisit and expand on recent analyses that use country-level data on climate and output to estimate the future economic impacts of climate change. We use an updated panel dataset on country-level rates of growth in per capita GDP paired with data on temperature and precipitation[5] to study whether contemporaneous and lagged temperature shocks affect GDP growth rates. Our approach uses within-country variation over time in temperature and GDP growth and controlling flexibly for a host of time-invariant and time-varying factors that could be correlated with both GDP growth and temperature. We then combine these estimated historical relationships between temperature and GDP growth with output from an ensemble of global climate models that project future changes in temperature under different emissions scenarios. This allows us to project potential impacts on country and global economic output, under the assumption that the economic impacts of a given amount of future warming are similar to the impacts of the same amount of historical temperature variation. We project impacts of warming on future growth rates, relative to a counterfactual world where temperatures are fixed at recent values, and integrate over time to estimate aggregate impacts on output at both the country and global level, accounting for uncertainty in both the historical econometric estimates as well as in the climate model estimates of future warming.

From this exercise, we estimate large possible impacts of future warming. Under a more conservative approach where temperature is not allowed to have lagged effects on growth rates, we find that global economic output could be 10 percent lower in 2100 relative to a world that did not warm beyond today's temperatures. Under a model that allows lagged temperature shocks to affect contemporaneous growth—a model that appears more consistent with the data—, we

3. See Rennert and others (2022), U.S. EPA (2022).

4. See Dell and others (2012), Burke and others (2015), Kalkuhl and Wenz (2020), Burke and Tanutama (2019), Nath and others (2023), Bilal and Kanzig (2024).

5. See Burke and others (2023).

estimate that global economic output could be 30 percent lower by 2100 relative to a no-warming scenario. We thus conclude that large macroeconomic impacts of climate change are indeed possible.

However, are such impacts plausible? Or do they require making claims about future growth rates that are wholly inconsistent with observed historical behavior of growth rates? As one way of assessing plausibility, we compare our projected impacts of climate on growth rates to observed historical variation in growth rates and to a recent Bayesian econometric model of international growth dynamics that was trained on historical data and used to project plausible future growth rates, absent climate change, over the next century and beyond.[6] This comparison cannot tell us whether climate change can or will have impacts as large as we suggest but allows us to ask whether the finding of large impacts requires assumptions on future growth impacts that push growth rates well outside their historical bounds. This is a somewhat conservative test, given that there is no reason, in principle, to believe that climate change could not generate ahistoric outcomes for which historical experience is a poor guide. However, we find that for most countries, the projected difference between growth rates under climate change and in a counterfactual world without climate change is within both historical variation as well as projected ranges in future growth rates by Müller and others (2022). We thus conclude that for most countries, growth impacts are historically plausible. In the hottest countries where we project future growth impacts to be largest, such as some countries in the African Sahel and Middle East, our projected impacts do appear to push growth rates outside of their historical range. We discuss whether such impacts could be consistent with other impact mechanisms identified in the existing climate literature.

1. Data and Empirical Approach

To estimate the relationship between variation in temperature and economic output, we follow earlier work[7] and use panel fixed effects regression to isolate the contribution of annual temperature fluctuations to variation in growth in real per capita GDP, by using national accounts data on country-level GDP from 1961 to 2019. Specifically, we estimate distributed lag panel fixed effects models of the form:

6. See Müller and others (2022).
7. See Dell and others (2012), Burke and others (2015, 2023).

$$g_{it} = \sum_{k=0}^{n} f(T_{i,t-k}, P_{i,t-k}) + \alpha_i + \mu_t + \theta_i \cdot t + \theta_i \cdot t^2 + \varepsilon_{it} \quad (1)$$

where g_{it} is the first difference of the natural log of real per capita GDP in country i and year t, using data in World Bank (2022). α_i is a vector of country fixed effects that account for any time-invariant differences between countries; μ_t is a vector of year fixed effects that account for any shocks or trends in either temperature or growth that are common across countries, such as macroeconomic shocks; $\theta_i \cdot t$ and $\theta_i \cdot t^2$ are country-specific quadratic time trends that additionally flexibly control for locally-trending variables that could be correlated with both temperature and growth. To estimate the function $f()$, we again follow earlier work[8] and use a parsimonious quadratic function to allow growth to respond nonlinearly to temperature and precipitation:

$$f(T_{i,t-k}, P_{i,t-k}) = \beta_{1,k} T_{i,t-k} + \beta_{2,k} T^2_{i,t-k} + \lambda_{1,k} P_{i,t-k} + \lambda_{2,k} P^2_{i,t-k} \quad (2)$$

This specification allows the effect of warming to depend on temperature levels, which can be seen by taking the derivative of equation (2) with respect to temperature. Prior work has shown that the temperature-growth relationship is well approximated with a concave quadratic function and that this relationship is in turn consistent with a host of microeconometric estimates of temperature impacts in various sectors of the economy.[9] We use data on annual country-average temperature and precipitation data from ERA5-Land,[10] a global monthly 0.1-degree gridded dataset with temperature, precipitation, and other climate variables. We compute country-year average temperature T_{it} by aggregating the native 0.1-degree data to the country-year level by taking the population-weighted mean over grid cells and months, using population data from the Gridded Population of the World dataset.[11]

To understand whether the data are consistent with "level effects", in which output returns to its previous trajectory in the years following a temperature shock, or "growth effects", in which output is permanently lower following a temperature shock, we again follow earlier work[12] and estimate distributed lag models where we

8. See Burke and others (2015, 2023).
9. See Burke and others (2015).
10. See Muñoz-Sabater and others (2021).
11. See CIESIN (2018).
12. See Dell and others (2012), Burke and others (2015).

model growth as a function of contemporaneous and multiple lagged values of temperature and precipitation. The sum of contemporaneous and lagged effects provides evidence into whether the effects of a temperature shock on output are persistent or transitory in nature: contemporaneous and lagged effects that sum to zero indicate level effects, whereas effects that do not sum to zero are consistent with growth effects. Given that we are estimating a nonlinear temperature response function, we test for level versus growth effects by evaluating the sum of marginal effects (current and lagged) at each point in the temperature distribution. In this analysis, we estimate distributed lag functions out to five lags. In the work on which this paper builds, functions are estimated out to ten lags and also compared to local projections approaches to estimating the impacts of shocks.[13]

To project climate damages, growth in each country in each future year is calculated as $g_{it} = \eta_{it} + \delta_{it}$, where η_{it} is the assumed baseline secular rate of growth absent climate change, and δ_{it} is the growth impact of warming, calculated as:

$$\delta_{it} = f(T_{it}) - f(\overline{T}_i) \tag{3}$$

using the estimated zero-lag or five-lag response functions estimated by equation (1). Here, $\overline{T}_i$ represents the baseline (2010–2020) average temperature in country i, and T_{it} the projected future temperature in year t in that country. We calculate T_{it} using a set of 30 global climate models run under the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which together ran the same set of prescribed emissions experiments. In each future year, we calculate the projected temperature in each country from each model and then take the median across models to get the median projected temperature change in that year. To avoid level biases in climate model output, we follow the customary approach and "de-bias" climate model projections by computing differences between model predicted temperature in year t and predicted temperature in the base years (2010–2020), and then applying these temperature differences to the observed baseline temperature to compute the time series of future temperatures in each country. This time series is then used in equation (3) to compute growth decrements at the country-year level.

13. See Burke and others (2023).

GDP per capita in each future country-year through 2100 is then calculated as:

$$GDPcap_{it} = GDPcap_{it-1}(1 + \eta_{it} + \delta_{it}) \quad (4)$$

with GDP/cap initialized in the base year using observed recent values. Aggregate damages are then computed by running this computation twice, once as above and once where δ_{it} is set to zero in a no climate-change scenario. The annual difference in per capita incomes between these two scenarios is then multiplied by projected population totals to get total climate-change impacts on GDP, is summed across years to get country-level impacts, and is then summed across countries to get global impacts. More details on this basic approach are provided in Burke and others (2023).

2. Results

2.1 Empirical Relationships between Temperature and Growth

The left panels of Figure 1 show the results of estimating equation (1) with either zero or five lags. In the zero-lag model, in which growth in year t can only be shaped by temperature in year t, the marginal effect of warming (the derivative of the response function) is positive for countries with average temperatures below about 13ºC and negative for countries with temperatures above that. This finding is consistent with earlier published evidence.[14] In the five-lag model—i.e., the model where the growth rate in year t can be affected by temperature shocks in years $t-5$ to t—we find a flattening of benefits at the cold end of the temperature distribution and an amplification of negative impacts at the hotter end of the distribution. These findings suggest that positive temperature shocks yield immediate benefits in cold places that then dissipate within a few years and yield persistent negative shocks to growth for most other countries in the world that grow over time, with cumulative impacts getting more negative the hotter the country was to start with. As shown in Burke and others (2023), the marginal effects from the five-lag model are significant and negative for all countries with average temperature above about 15ºC. Also shown in that paper

14. See Burke and others (2015).

is the fact that these response functions are robust to a range of other controls, fixed effects, and datasets, and that they appear to be fairly stable over the last 60 years, implying limited adaptation to date.

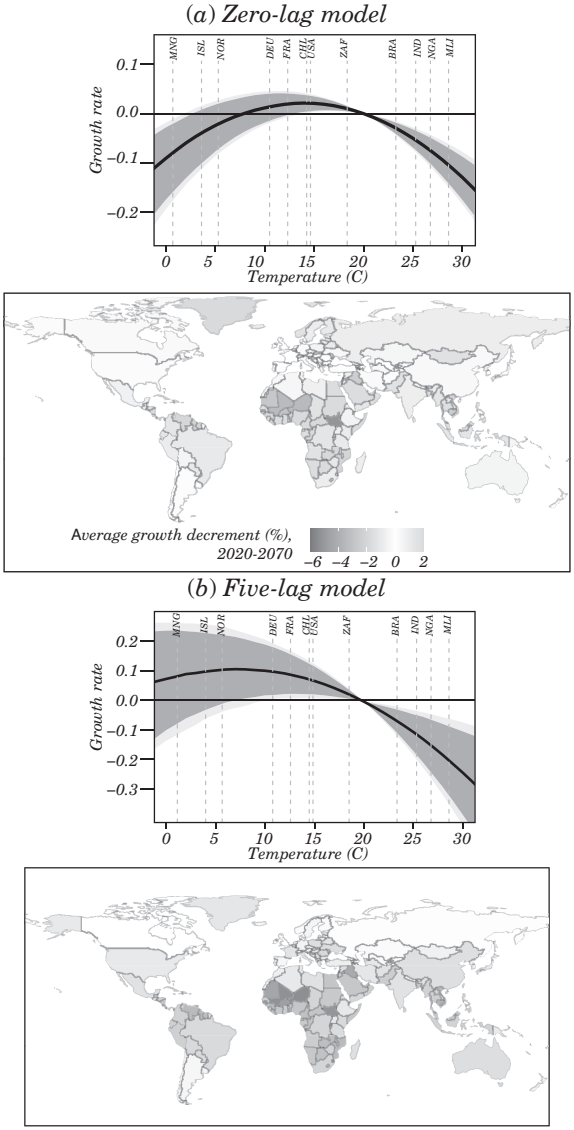
2.2 Effects on Future Growth and Output

We combine these historical econometric estimates with output from an ensemble of global climate models to project future impacts on growth rates at the country level and future impacts on the level of output by 2100. The right panels of Figure 1 show estimated impacts of warming on future growth rates at the country level, using the SSP3-7.0 warming scenario (a middle-to-high warming scenario), where calculated as the average decline in growth rates due to warming over the next 50 years (2020–2070)—i.e., the average value of δ_{it} from equation (3). Projected impacts are more negative in the tropics, which are hot to begin with, and are more negative in the five-lag model as compared to the zero-lag model. In the zero-lag model, we estimate that growth would slow by a modest 0.1–0.3 percentage points in many large economies (U.S., China) and could increase by that amount in colder parts of the European Union. In the hottest parts of the tropics, the zero-lag model predicts that growth could slow by 2–3 percentage points annually.

In the five-lag model, we estimate that growth could slow by 1–1.5 percentage points across many large economies and cooler regions (U.S., China, much of the EU, Chile) on average over the next 50 years, and that growth could slow by as much as 3–4 percentage points in much of the tropics including Latin America, Africa, the Middle East, and parts of South and Southeast Asia, and above 5 percentage points in the very hottest regions. In the zero-lag model, many higher-latitude countries experience modest benefits from warming. In the five-lag model that allows for delayed impacts, these benefits dissipate in all but the very coldest countries (e.g., Mongolia).

Based on these growth rate impacts, we project global aggregate impacts on GDP, expressed as the percentage difference in global GDP in a world that did not warm beyond 2020 versus a world that warmed at different rates, as projected by different emissions scenarios used by the IPCC. We propagate uncertainty in projected global damages by combining uncertainty in both the econometrically estimated relationship between temperature and warming from historical data as well as the cross-model uncertainty in future warming (given emissions), as revealed by the ensemble of global climate models that we use.

Figure 1. The Impact of Temperature on Country-Level Growth Rates



Source: Authors' calculations.

Notes: Left plots show the estimated relationship between country annual temperature and country growth rates, using historical data from 1961–2019. Top panel shows the zero-lag model and bottom panel, the five-lag model. Vertical dotted lines indicate today's average temperatures for selected countries. Maps show predicted growth rate impacts under future climate change, averaged over the next 50 years, using either the zero-lag (top) or five-lag model (bottom) to project impacts. Estimates represent the difference in annual growth in GDP/capita in a world with climate change versus a world without climate change, averaged over the years 2020–2070.

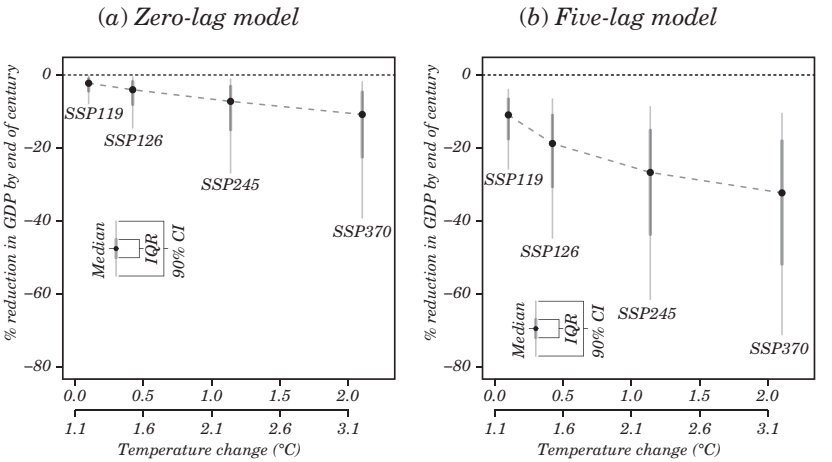
Estimated impacts are shown in Figure 2 using both the zero-lag and five-lag response functions and computing damages across emissions scenarios that range from highly ambitious and perhaps currently implausible (e.g., SSP1-1.9 and SSP1-2.6 that both limit warming to below about 1.5ºC by 2100) to fairly ambitious (SSP2-4.5, which limits warming to between about 2–2.5ºC) to more pessimistic (SSP3-7.0, which results in about 3ºC of global warming). Updated estimates suggest that, given recent emissions trends and policy commitments, the world is on track for 2–3ºC of warming by 2100.[15] We find that damages grow roughly linearly with projected warming, with damages reaching roughly 10 percent of global GDP in 2100 under SSP3-7.0 using the zero-lag model and reaching 30 percent of global GDP under the same scenario using the five-lag model.

These estimates contrast with headline estimates from earlier published work[16] in two ways. First, point estimates of impacts, particularly for the zero-lag model, are somewhat smaller, a result of progress on emissions mitigation and thus lower projected warming by 2100 as compared to a decade ago. Second, unlike previous work, confidence intervals on projected impacts do not contain zero—a result of substantially less econometric uncertainty in temperature growth relationships using updated data. This is particularly true for the five-lag model, which is substantially less noisy using updated data and implies much more negative (and statistically significant) impacts.

Companion work[17] calculates the social cost of carbon (SCC) implied by these aggregate damages by using a range of assumptions about discounting, secular growth rates, and time horizons over which damages are allowed to accumulate. Using the zero-lag model, Ramsey discounting calibrated to near-term rates and an impact horizon that ends in 2100, the SCC is found to be around USD 200. Using the five-lag model under the same assumptions, SCC estimates are substantially higher—roughly USD 1400 per ton. Higher discount rates yield lower SCC estimates—for instance, USD 125 for a 3 percent discount rate under the zero-lag model. Lower discount rates or longer impact time horizons (e.g., through 2300 instead of 2100) can yield substantially higher rates, with the highest estimates coming when growth effects are assumed to cumulate through 2300—the time horizon used in recent U.S. regulatory analyses.[18]

15. See van de Ven and others (2023).
16. See Burke and others (2015).
17. See Burke and others (2023).
18. See U.S. EPA (2022).

Figure 2. Projected Impact of Future Warming on Global GDP by 2100, under Different Emissions Scenarios and Two Econometric Models



Source: Authors' calculations.
Notes: Left panel: projected impacts using the zero-lag model, under four different emission scenarios. Predicted changes in global temperature from each scenario are shown on the x-axis and estimated changes in global output (relative to a world that did not experience warming) on the y-axis. Confidence intervals account for both econometric and climate model uncertainty. Right panel: as in left panel but for five-lag model.

There is no question that all of these estimates are large. Given current global annual CO_2 equivalent emissions of 50 billion tons, the lower estimates would imply that current annual emissions generate USD 10 trillion in discounted damages every year, or about 10 percent of current global GDP. The higher SCC estimates imply annual discounted damages from annual emissions exceeding 50 percent of current GDP.

2.3 Are These Impacts Plausible?

2.3.1 Comparison to Existing Damage Estimates

We assess the plausibility of our impact projections in three ways. The first compares our estimates of projected climate impacts to recent independent impact projections. One simple point of comparison is the estimates of the SCC. Our zero-lag estimate of an SCC of around USD 200 is very similar to multiple recent "bottom-up" econometric

estimates of the SCC that informed recent U.S. policymaking[19] and are near the median of an earlier expert elicitation of the SCC.[20] Our much higher estimates from the five-lag model are only slightly larger than those found in recent a global econometric exercise[21] and are also consistent in magnitude with bottom-up estimates that use equity weights to account for differential impacts in low-income countries.[22] These comparisons do not indicate our estimates are correct, but they suggest that our results are no longer the empirical outlier that earlier versions of our estimates[23] were deemed to be. Put simply, others have recently arrived at similar damage estimates, albeit through different pathways.

2.3.2 Comparison to Variation in Historical Growth

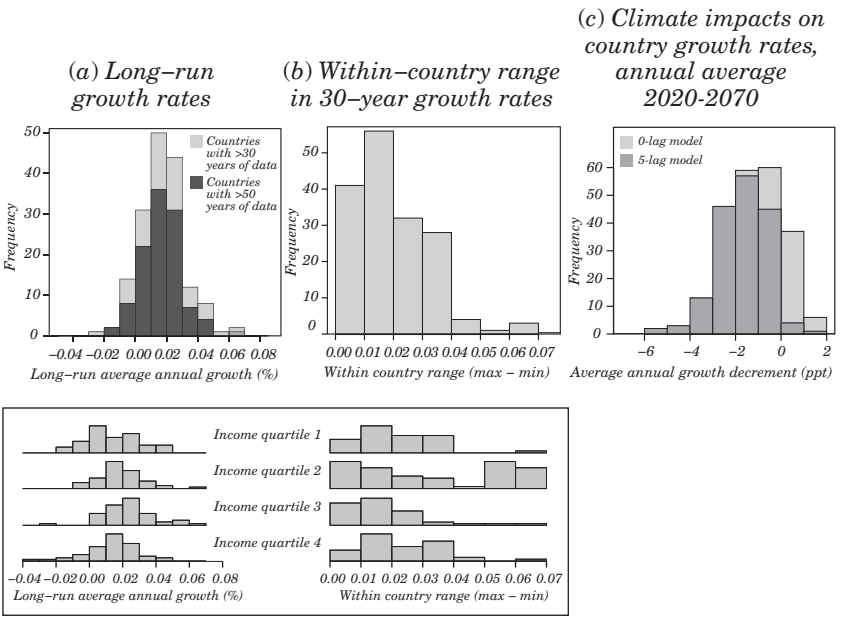
Our second approach to assessing plausibility examines whether the impacts of future climate change on growth rates that we predict are small or large relative to the historical variation in long-run growth rates that has been observed. Given the large number of non-climatic factors that are important in economic growth, a prediction that climate change alone might push growth rates outside their historical distribution could appear implausible, even if not impossible. As an example, if a country had grown at a real annual rate between 1–3 percent for over a century, or based on historical data is projected to grow at something close to that rate in the future and then we predicted that climate change would reduce annual growth in that country below 0 percent, then the implicit argument is that climate change is substantially more important than all other factors in future growth—an assumption that many might view as implausible for advanced economies in particular, even if in principle it cannot be ruled out.

Figure 3 uses World Bank data on real per capita growth rates to characterize variation in long-run growth rates around the world since 1960. The data show substantial variation in average long-run growth rates across countries, with some countries shrinking on average over the period and others growing by over 5 percent per annum.

19. See Rennert and others (2022), U.S. EPA (2022).
20. See Pindyck (2019).
21. See Bilal and Kanzig (2024).
22. See Nath and others (2022).
23. See, for example, Burke and others (2015).

The distribution looks similar if we restrict the sample to countries that report data for at least 50 years since 1960. Distributions remain wide even if we look within quartiles of the income distribution. The data clearly show that different countries can grow at very different rates over long periods.

Figure 3. Between- and Within-Country Variation in Long-Run Growth since 1960, and Projected Climate Impacts on Growth Rates



Source: Authors' calculations.

Notes: Left column of plots show variation in long-run country-average annual growth rates, computed as the average annual growth rate of real per capita GDP in each country over all available data in that country, restricting to countries with at least 30 years of data (grey) or 50 years of data (dark grey) since 1960. Histograms at bottom show the same data but by quartiles of per capita income. Center column of plots show within-country variation in 30-year-average growth rates, estimated by computing, for each country, a 30-year rolling mean of per capita growth rates in that country and then taking the range by country. For instance, a value of 0.02 would indicate that in a given country, the max 30-year growth rate was 2 percentage points higher than the min 30-year growth rate. Bottom histograms again show distributions by quartile of the per capita income distribution. Right panel shows distribution of predicted climate impacts on annual growth rates from our analysis, averaged over the next 50 years (2020–2070), for the zero-lag and five-lag models. For instance, a value of -2 indicates a predicted growth rate that is 2 percentage points lower under climate change than under no climate change, averaged over 50 years.

To complement these between-country comparisons, we then look at within-country variation in long-run growth rates. We first compute, for each country, a 30-year rolling mean of average per capita growth rates over all available data for each country and then compute the within-country range in these 30-year means. As shown in the right panels in Figure 3, we find substantial within-country variation in long-run (30-year) growth rates, and large variation is observed across all countries as a whole as well as when looking at income-quantile groupings. The average range in within-country 30-year growth rates is about 1.9 percentage points, the median is 1.8 percentage points, and the 25th and 75th percentiles are 1 percentage point and 2.7 percentage points. This implies that since 1960, a large majority of countries have experienced one 30-year period where growth was at least 1 percentage point higher per year than another 30-year period, and about half of all countries have experienced differences twice that large. Our conclusions from this simple descriptive analysis are consistent with a very large literature on cross-country growth:[24] countries can grow at very different rates for long periods of time within their own history, and two different countries (even with similar initial incomes) can grow at very different rates for very long periods.

How large are our predicted future growth decrements from climate relative to the within- or between-country range in observed growth rates over the last half century? The right panel of Figure 3 shows the distribution of predicted impacts of climate change on country growth rates across countries—essentially, a histogram of the rates plotted in the maps in Figure 1. For the zero-lag model, the median annual growth decrement from climate change over the next 50 years is 0.7 percentage points, and the 25th percentile is -1.4 percentage points. For the five-lag model, the median is -1.6 percentage points and the 25th percentile is -2.3 percentage points. These numbers imply that, for instance, if the set of countries had grown at 2 percent with no climate change, we would predict that the median country would instead grow at an average rate of 1.3 percent over the next 50 years with the zero-lag model, and 0.4 percent under the five-lag model. These decrements are no doubt large, but the resulting values are well within both the observed between-country variation in long-run growth rates, as well as the observed within-country variation over the last 60 years.

24. See, for example, the recent review by Johnson and Papageorgiou (2020).

2.3.3 Comparison to Müller, Stock, and Watson Estimates

In much more sophisticated recent work, Müller, Stock, and Watson (2022) (hereafter MSW) build an econometric model of historical growth dynamics, discipline the model on a range of historical data and use this model to project the range of future growth rates possible at both a global and country level. Although climate is not an explicit factor in the model (the model is purposely agnostic on the sources of growth), to the extent that an already-warming climate has influenced historical growth rates, the modeling exercise can perhaps be construed as implicitly subsuming the historical influence of climate on growth and then holding that influence fixed. Consistent with the simplistic analysis of historical data above, MSW find that countries can grow at different rates for very long times (decades or centuries) and that they can experience prolonged periods of faster growth and prolonged periods of growth collapse.

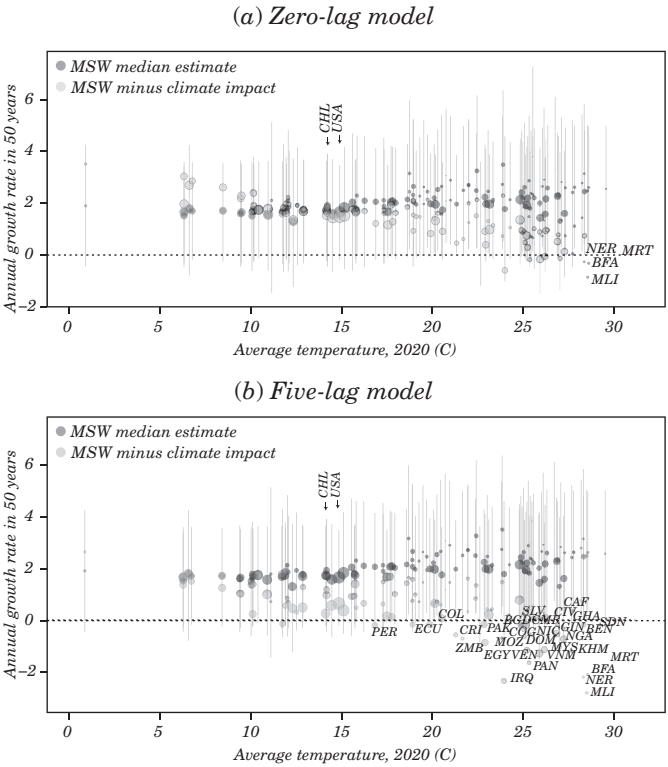
The range of projected future growth rates from MSW allows another check on whether our predicted decrements to growth from climate change are far outside the bounds of possible variation in growth rates from non-climatic factors. In Figure 4, we compare MSW's projected country-average growth rates over the next 50 years to our projected growth rates over the same period if we had taken the MSW median as our estimated secular rate and then adjusted these rates up or down as a result of climate change. We plot our climate-impacted average growth rates on top of MSW median and 5th to 95th percentile estimates of country growth rates. Data are available for 111 countries in the MSW data.

In the zero-lag model, growth rates are amplified under climate change for a small set of countries on the cold end of the temperature distribution, but all climate-adjusted growth rates are well within MSW's uncertainty bounds on secular growth rates. For hotter countries, growth decrements are negative and increasingly large and fall outside MSW bounds for four of the hottest countries in our dataset, all of which are in the African Sahel. Thus in this model, about 4 percent of countries have climate-impacted growth rates outside MSW's secular bounds on what growth rates could be.

In the five-lag model, very few countries are projected to benefit from warming. Nearly all countries are harmed, and some very substantially. Under this model, we find that 31 countries now fall outside the MSW bounds (or 28 percent of countries in the MSW data), including Sub-Saharan African, Asian, and Latin American

countries across the tropics, as well as a handful of very hot countries in the Middle East. Most large economies, and all economies in more temperate latitudes, remain inside the secular uncertainty bounds.

Figure 3. Between- and Within-Country Variation in Long-Run Growth since 1960, and Projected Climate Impacts on Growth Rates



Source: Authors' calculations.

Notes: MSW projected median (black dot) and range (whiskers) of country-level growth rates over the next 50 years, with countries sorted horizontally by average temperature today. Orange dots (top panel) or red dots (bottom panel) are predicted growth rates under climate change, calculated by adjusting the MSW median estimates by predicted growth impacts of climate change using either the zero-lag (light grey) or the five-lag (dark grey) model. Countries are labeled if their projected growth rate under climate change is outside the range of MSW estimated secular growth rates. Chile and the U.S. are also labeled. Dots are scaled relative to the total GDP of the country.

What does this tell us about the plausibility of our estimates? While there is no clear reason why it would be impossible for climate change to push countries completely outside their secular growth experiences or trajectories, doing so would require climate to be the dominant factor in growth—a proposition that many might find implausible. However, we find that our estimates for climate-impacted growth rates for the large majority of countries—and all large economies that account for the lion's share of global GDP impacts we measure—fall inside MSW's data-driven estimates of their secular bounds. This perhaps suggests our estimates are plausible: MSW's numbers suggest these countries could experience similar growth rates even without climate change.

What about the few dozen tropical and largely lower-income countries that fall outside projected secular bounds? Is there a plausible story that would link future changes in climate to growth collapses in those countries? The literature identifies a few possibilities. One well-studied effect relevant for agriculturally dependent economies is the highly nonlinear relationship between temperature and productivity of key crops. Multiple careful econometric studies suggest that warming in this century, which would push exposure to "killing degree days" well outside the historical distribution of exposures, could reduce the productivity of these crops by over 50 percent.[25] A second and perhaps related channel is the observed link between warmer temperatures and various types of human conflict.[26] In this work, small increases in temperature are observed to generate very large increases in the risk of civil conflict in the tropics. Other work has shown that such conflict can be incredibly and persistently damaging to economic output.[27] Finally, Dell and others (2012) show how hot temperatures can destabilize political institutions in low-income countries and use that fact to help explain the large impact of temperature on growth they find in these countries. Ongoing and protracted low-growth episodes or growth collapses are readily observed around the world in conflict-prone and climate-vulnerable countries, including Somalia, Haiti, South Sudan, Afghanistan, Yemen, Libya, Syria, Chad, and the Central African Republic. These mechanisms and examples thus offer three possible stories for how future unprecedented changes in climate could dominate growth trajectories in agriculturally dependent or conflict-prone countries, although their realization is by no means preordained.

25. See Hultgren and others (2022), Schlenker and Lobell (2010).
26. See Hsiang and others (2013).
27. See Cerra and Saxena (2008).

2.3.4 Do Our Estimates Violate Convergence?

A voluminous literature in economics has argued about whether countries converge to similar growth rates or to similar levels of income over the long run.[28] MSW suggest that convergence is observed, but for many countries happens on multi-decadal or century-long time scales, and that countries can grow at different rates for very long periods of time. A large body of related work—summarized in Johnson and Papageorgiou (2020)—finds that if convergence is happening, it is likely happening in "convergence clubs", or within countries that grow at similar rates or converge to similar income levels. The idea is that even if there is no clear evidence of a global force that keeps all country incomes moving together, there are both theoretical and empirical reasons to think that certain sets of countries might move similarly. Because nothing in our impact projections forces country growth rates or income levels to move together or converge, either globally or in groups, a concern might be that our climate-change projections could generate a divergence in incomes that is inconsistent with theoretical or empirical notions of convergence. This concern has been raised by Nath and others (2023).

To assess this concern, we examine the "OECD club", a set of advanced economies estimated to exhibit conditional convergence in MSW, which currently accounts for over half of global output. Figure 5 characterizes the evolution of per capita incomes in OECD countries over the next 50 years, comparing a world without climate change (in which countries grow at the median projected rate by MSW) to a world in which that rate is adjusted downward annually due to the impact of climate change, as estimated by our five-lag model. As shown in the Figure, incomes in the climate-affected world are lower than in the non-climate-affected world, as expected, but we find that both the range and variance of incomes after 50 years are *smaller* in the climate-affected world than in the non-climate-affected world. For instance, the standard deviation of per capita incomes is USD 39,000 in the non-climate-affected world and USD 37,000 in the climate-affected world, and the difference between highest and lowest incomes is 25 percent higher in the non-climate-affected world. As another comparison, we estimate that the standard deviation of 50-year-average historical growth rates across our OECD sample is 0.8 percentage points, whereas it is 0.4 and 0.5 percentage points

28. See Johnson and Papageorgiou (2020).

over the next 50 years among the same countries in our zero-lag and five-lag estimates, respectively.

While these are just a few possible lenses through which convergence can be assessed, and other tests could yield different insights, we provisionally conclude that our projections are no less consistent with convergence in income growth and levels than state-of-the-art projections of future income levels absent climate change or recent observed variation in long-run income growth among OECD countries.

3. Concluding Remarks

We combine historical data on temperature and growth from the last 60 years with projections of future climate change from an ensemble of climate models and estimate large potential impacts of climate change on global economic output. Our estimated damages are large relative to earlier estimates from integrated assessment models[29] but are more similar to recent empirical approaches that use a variety of data and empirical strategies to estimate damages.[30]

We assess the plausibility of our estimates in a number of ways, including by comparing them to these recent independent estimates, as well as by comparing them to historical and projected future variation in growth rates absent climate change. This allows for a heuristic test of whether, in order to generate the magnitude of impacts we predict, climate change would have to generate either variation in growth rates that is unobserved in historical data or variation that is outside the bounds of likely variation in growth predicted by a sophisticated growth model disciplined by historical data. For most countries in the world, we find that our predicted growth impacts from climate change are within the "secular bounds" of non-climate growth experience—that is, variation as large or larger than what we predict is routinely observed. For countries where predictions fall outside these bounds, we point to existing evidence and historical examples that could lend plausibility to growth collapses.

Does this analysis mean we can be certain that climate change will have as large an impact on global output as we suggest? No. Does it suggest that the growth rate impacts we estimate should be considered implausible because they clearly diverge from patterns

29. See Revesz and others (2014).
30. See Rennert and others (2022), U.S. EPA (2022), Bilal and Känzig (2024).

or variations in growth rates that have been observed historically? Also no. Our calculations, and those done by others, suggest that very large macroeconomic impacts from climate change are possible. Our analysis here suggests that the growth effects that generate these large impacts are historically plausible.

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Through Drought and Flood: Past, Present, and Future of Climate Migration

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The greatest destructions of mankind have been
brought about by drought and flood
"*Timaeus*," *Plato* (*ca. 360 BCE*)
The lingering cold spells left the pastoralists
no other choice but to [. . .] migrate
to warmer regions and to [. . .] plunder for their own food.
The domino effect was felt [. . .] outside the cold spell
[. . .] much more than
[where] the cold spell [. . .] were the most severe.
Ronnie Ellenblum (2012)

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Migration from low-income countries has doubled in the last 30 years, a flow increasingly associated with climate degradation in nations heavily dependent on agriculture. This process is often confounded with weak institutions, violence, and strife. Countries at the receiving end have also been affected. With an increasingly negative perception among the general population, migration has contributed to social and political polarization associated with the recent deterioration of the geopolitical landscape. However, the scale of migration thus far will likely pale in comparison with future pressures. As climate further deteriorates, the map of uninhabitable ecosystems—many of which house some of the largest concentrations of people today—will continue to expand. Regions that will suffer the most are often those already degraded, suggesting observed trends may soon become highly nonlinear.[1] Thus, mass migration—the main adaptation mechanism of our species to survive climate change in the past—may constitute a key social tipping point in our modern, overpopulated societies.

This paper aims to study the emigration pressures associated with climate change and sheds light on how it might evolve as climate degrades further under different future scenarios. A key challenge to performing this analysis is that available data on migration goes a few decades back, a period over which the planet has seen a moderate increase of 1.2 degrees Celsius (°C), which seems not to be a significant enough period to fully capture the potential highly nonlinear relationship between environmental degradation and migration.

Considering this limitation and as motivating pieces for our empirical work in the following sections, we start the analysis by performing a narrative approach focused on four events from the past that we consider as informative case studies about the potential relationship between climate events, environmental degradation, migration flows, and social/institutional dislocations. The four historical events we focus on are: the end of the Bronze Age (circa 1200 BCE); the collapse of the Eastern Mediterranean (circa 1000 ACE); the Bhola Cyclone, the Indo-Pakistani War, and the creation of Bangladesh (1971); and the Rwandan genocide and the conflict in the Congo Basin (1994–2001). Relying on noneconomic sources, we document that severe climate disruption has led to significant outward migration in the past, driven by social conflict, violence, regime change, and, in some cases, societal collapse.

1. See the IPCC Sixth Assessment Report (AR6) for a detailed explanation.

Then, we turn the analysis to the present. To shed light on the current relationship between climate events and outward migration, we perform a quantitative analysis relying on international census data from the United Nations available for 154 countries between 1990 and 2020. Regarding climate data, we identify the maize growing season using data from the FAO, and then we calculate the annual average temperature for those periods for each country. Using this panel data, first, we explore the relationships between the growth of the emigration stock and the average temperature at country level. Classifying countries by their type of climate (i.e., cold, arid, temperate, tropical), we observe that tropical countries are the ones with the most significant growth in the emigration stock between 1990 and 2020, but at the same time, exhibit the smallest temperature increase.

In contrast, cold countries are those experiencing the larger increase in average temperature but the smallest growth of emigration stock. Given that the initial average temperature in tropical countries in 1990 was 24°C, much higher than the 15°C from the cold countries, this simple comparison suggests a nonlinear component in the relationship between emigration and temperature. We understand this result as suggestive evidence that a marginal temperature increase in already warm countries produces more damage and incentives to emigrate than the same marginal temperature increase in cold countries.

Next, to formalize the analysis, we perform a panel regression approach that relates emigration stock growth with temperature and precipitation. Similar to Missirian and Schlenker (2017), we estimate a reduced-form model including country- and time-fixed effects, but we extend the analysis by including GDP per capita as an additional explanatory variable that interacts with the climate variables.[2] This allows us to capture the adaptation channel through which richer countries should be able to spend more resources in ameliorating the damages from climate change, thus reducing the pressure on its inhabitants to emigrate. The results show a highly significant and nonlinear relationship between climate change and migration, with a U shape around a "temperature optimum." Nonlinearity is stronger in poorer countries. Indeed, despite tropical climatic zones having experienced the smallest increase in temperature thus far,

2. Also, Missirian and Schlenker (2017) use data on asylum applications to the European Union. In contrast, we use international census data that accounts for the migratory outflows to all the countries in the world.

they exhibit the most significant increase in outward migration due to their higher initial temperature and lower GDP per capita, which limits their adaptation capabilities.

Finally, we use the previously estimated model to project future emigration under five Intergovernmental Panel on Climate Change (IPCC) scenarios and an Atlantic Meridional Overturning Circulation (AMOC) collapse scenario. The results show moderate effects on emigration increase under moderate IPCC climate scenarios, but it almost doubles for tropical areas in the most extreme IPCC scenario. Regarding the AMOC scenario, the temperature projections show that, while the tropical countries will become warmer, the northern European countries will become colder, translating into an increasing outward migration for both groups of countries. In this tipping-point scenario, the projections show a five-time increase in total outward migration in the world after the AMOC collapse, going from 200 million in 2020 to 1 billion in 2100. We conjecture that our results constitute a lower bound of the possible effects, given (i) the non-well-captured nonlinearities and (ii) the potential fall in income due to climate damages that limit adaptation.

1. Related Literature

Migration decisions can be influenced by the effect of climate change on the economic and social performance of countries. Carleton and Hsiang (2016) provide an excellent review of the state of the art on this topic. They highlight key methodological innovations and results describing the effects of climate on health, economics, conflict, migration, and demographics. Regarding the economic drivers, one of the most studied channels is the climate-related decline in agricultural productivity. Several works have addressed this relationship at country level, finding that the increase in extreme weather events (i.e., floods and droughts) has negative impacts on the productivity in this sector—e.g., Auffhammer and others (2012), Auffhammer and Schlenker (2014), Lobell and Burke (2008), Schlenker and Roberts (2009), Welch and others (2010). Regarding labor productivity, there is also growing evidence that increasing temperatures are negatively affecting the ability of workers to perform their tasks around the world due to heat stress—e.g., Hsiang (2010), Heal and Park (2015), Graff Zivin and others (2018), Graff Zivin and Neidell (2014), Somanathan and others (2021). Burke and others (2015b) provide evidence that economic activity in all regions is being affected by the global climate

due to a decline in agricultural and labor productivity and, if future adaptation mimics past adaptation, unmitigated warming is expected to reshape the global economy by reducing average global incomes roughly 23 percent by 2100. They also find nonlinear responses conditional on the countries' income level, which would lead to an increase in global income inequality relative to scenarios without climate change.

Regarding socio-political drivers, existing literature has shown that increasing temperatures and more frequent extreme weather events relate to a higher likelihood of social unrest. Hsiang and others (2013) find that deviations from normal precipitation and mild temperatures systematically increase the risk of conflict. Assembling and examining studies from different social fields post 1950, they find that the influence of climate on modern conflict is substantial and statistically significant. Each 1-SD change in climate toward warmer temperatures or more extreme rainfall increases the frequency of interpersonal violence by 4 percent and intergroup conflict by 14 percent (median estimates). They conclude that, given the large potential changes in precipitation and temperature regimes projected for the coming decades—with locations throughout the inhabited world expected to warm by 2 to 4 SDs by 2050—, amplified rates of human conflict could represent a large and critical social impact of anthropogenic climate change in both low- and high-income countries. Similarly, by analyzing the results form 55 previous studies, Burke and others (2015a) find that deviations from moderate temperatures and precipitation patterns systematically increase conflict risk. The contemporaneous temperature has the largest average impact, with each 1-SD increase in temperature increasing interpersonal conflict by 2.4 percent and intergroup conflict by 11.3 percent.[3]

However, how the negative relationship between climate change and socioeconomic performance is translated into migration pressures is still a work-in-progress area of research. Despite a cross-country analysis seeming to be the most suitable approach to capture potential nonlinearities in this relationship, most of the work done so far is focused on studying the influence of climatic factors on human migration at country level because of data availability reasons. In this line, Feng and others (2010) examine the linkages among variations in climate, agricultural yields, and people's migration responses

3. For additional references, see Miguel and Satyanath (2011), Buhaug (2010), Reuveny (2008), and Bernauer and others (2012).

using state-level data from Mexico. They find a significant effect of climate-driven changes in crop yields on the rate of emigration to the United States, with a 10 percent reduction in crop yields leading to an additional 2 percent of the population to emigrate. Bohra-Mishra and others (2014), by following the province-to-province movement of more than 7,000 households in Indonesia over a decade and a half, find that an increase in temperature (e.g., due to natural variations or global warming) and, to a lesser extent, variations in rainfall are likely to have a greater effect on permanent outward migration of households than natural disasters.[4]

To the best of our knowledge, in the literature, there are just a few previous studies focused on understating the relationship between climate change and human outward migration from a cross-country perspective, which are the closest related to ours. Cattaneo and Peri (2016), using data from 115 countries between 1960 and 2000, analyze the effect of differential warming trends across countries on the probability of either migrating out of the country or from rural to urban areas. They find that higher temperatures in middle-income economies increased migration rates to urban areas and other countries. In poor countries, higher temperatures reduced the probability of migration to cities and to other countries, consistently with the presence of severe liquidity constraints. Missirian and Schlenker (2017) consider the effect of temperature fluctuations on refugees coming to the European Union from 103 source countries in the recent past (2000–2014). Similar to our results, they find a nonlinear relationship between emigration and temperature increases. More recently, Cruz and Rossi-Hansberg (2024) characterize migration and innovation as the main adaptation mechanisms for climate change. By developing a dynamic economic assessment model with high spatial resolution, they found heterogeneous welfare effects across countries. In particular, they find that countries in some parts of Africa and Latin America would face the largest losses and pressures for emigration.

Our contribution to this line of work is threefold. First, we extend the number of countries (154) and the time horizon (1990–2020) for the analysis, which should allow us to be more able to capture nonlinearities, considering that most of the temperature increase

4. Other related work is Marchiori and others (2012), which examines the effects of temperature and rainfall anomalies in sub-Saharan Africa, and Nawrotzki and others (2015), which investigates climate change impacts on U.S.-bound migration from rural and urban Mexico between 1986 and1999.

with respect to the pre-industrial era has happened in the last decade. In addition, we extend the analysis by including a group of historical events through a narrative approach that allows us to inform the nonlinear relationship between climate change and four migration episodes. These episodes were selected considering that the temperature changes that characterized them were much larger than the changes that we have seen so far in the present, which we understand as an imperfect mirror of what we might see in the future. Second, we incorporate the level of income interacting with temperature changes as a proxy for the ability of countries to adapt to the physical impacts of climate change. The results show that including this variable is key to addressing the heterogeneous effects across climate zones. Third, as in previous work, we used our estimated model to project future emigration under the Shared Socioeconomic Pathways (SSP) climate scenarios developed by the IPCC. However, we also study a tipping-point scenario related to the AMOC collapse. In contrast to the usual projections for the IPCC scenarios, where tropical countries are the most affected ones, under the AMOC collapse, cold and temperate countries show the largest outward migration flows.

2. The Past: Case Studies in Environmental Stress, Migration, and Social Dislocation

The relevance of climate and environmental stressors in affecting social dynamics has been extensively discussed in the literature, spanning from the disasters in Central Europe during the 17th century,[5] to the ebb and flow of warfare in Ancient China.[6] The link between climate and the environment with migration flows also has attracted significant attention, starting from the fact that early human migration out of Africa coincided with climate events.[7]

As motivating pieces for our empirical work in the following sections, we present four historical events that inform the potential relationship between climate events, environmental degradation, migration flows, and social/institutional dislocations.

In this section, we take a narrative approach, aiming to use these case studies as motivating episodes for the main empirical argument in subsequent sections. We recognize that this approach should be taken

5. See Parker (2013).
6. See Zhang and others (2007).
7. See Beyer and others (2021).

with several caveats. First, it relies heavily on noneconomic sources, by using historical, journalistic, and social science resources. Second, many of the topics addressed have not been settled in the relevant literature, so the assertions presented here should be taken as the authors' informed view regarding fields outside of economics. Thirdly, the arguments presented are naturally not structured to offer a formal identification strategy for finding causality, which is the bread and butter of empirical economics, but again, they are offered as motivating stories for the empirical work in follow-up sections.

Having said that, environmental stress and climate events have desirable characteristics for economic research. From the point of view of the affected societies, they can be considered an exogenous source of variation. Therefore, as historical phenomena are typically enmeshed in complicated multicausal and simultaneous relationships, climate and the environment provide a certain degree of identification. This allows us to illustrate the potential interactions from a broad set of phenomena that are seldom considered jointly in economics, and the just-mentioned exogeneity of climate can describe that. An original climate event shock or environmental degradation can end up severely impacting the livelihood of the affected communities. It occurs through economic impact, life-threatening prospects, or both, such as drought, famine, floods, and pestilence as common immediate occurrences. This initial impact can be amplified through social dislocation, rebellions, civil war, and general strife in the communities involved. Mass emigration is a result of communities escaping either a deteriorated livelihood or the violence that plagues the area. In this process, communities often carry their original social norms and informal institutions with them. Moreover, the military or civilian characteristics of these migratory waves cannot be easily distinguished, as there is no clear-cut distinction between soldierly and civilian migrating groups in pre-modern or fragile societies. Finally, this migratory wave can interact in the new host regions, sometimes creating their own social dislocation dynamics, thus provoking a "domino effect."

The idea that conflict can arise out of the arrival of migrants has been well-known since antiquity. Ancient Near Eastern cultures had a precise identification of the nature of migration flows, stating the differences between diplomatic or mercantile and refugees or invaders.[8]

8. See Beckman (2013).

The concept of xenophobia (fear of strangers), as its etymology suggests, was a well-recognized concept in Ancient Greece. A clear example is the Greek/Barbarian dichotomy, which was "ubiquitous in Ancient Greece" and based on multiple dimensions, such as language, intellect or knowledge, and pan-Hellenism.[9]

The four episodes we describe share most of the narrative just mentioned above. We take one episode of Antiquity—the end of the Bronze Age—, one from the Middle Ages—the societal collapse in the Eastern Mediterranean—, and two from contemporary times—the creation of Bangladesh after the Indo-Pakistani War of 1971 and the war in Africa that occurred after the Rwandan genocide in 1994.

2.1 The End of the Bronze Age (circa 1200 BCE)

By 1200 BCE, the different peoples of the ancient world, spanning from the Aegean to modern-day Afghanistan, had been experiencing the flourishing of the Bronze Age. Then, over a period of a few hundred years, catastrophic events led to the collapse of many of the significant actors that had progressively consolidated in previous ages.[10]

Upper and Lower Egypt had unified around 3000 BCE, and the Kingdom of Egypt had expanded southward into Nubia and westward towards the Levant. In Mesopotamia, the cradle of civilizations after Sumer and Akkad, the Assyrian and Babylonian empires rose as important power centers alongside smaller kingdoms. In Anatolia, the Hatti (Hittite) Empire had its capital close to modern-day Ankara and covered an expanse from the Euphrates River to almost the Mediterranean Sea. Further west, Mycenaean Greece was constituted by several city-kingdoms in the Peloponnese and Central Greece and across the Aegean in Asia Minor. In Crete, the Minoans constituted one of the earliest advanced civilizations, with large multi-level palaces decorated with their well-known frescoes.

These ancient civilizations achieved significant cultural advancements throughout the Bronze Age. For instance, the use of clay tablets became widespread, and the cuneiform script was adapted for communication and administrative recording in several of the languages spoken back then. In Greece and Crete, Linear B script provides the first evidence of written Greek language, used on clay

9. See Papanikos (2020).

10. Cline (2014) provides an overview of the events across the region and the scholarly debate on its causes.

tablets mainly for administrative records. The Bronze Age also saw, of course, the development of Egyptian hieroglyphs. Religious practices were established and reached higher levels of complexity. There were several religious systems, such as polytheism (e.g., gods of the classical Greece pantheon), in Mesopotamia, Egypt, and Mycenaean Greece. However, dualistic and monotheistic cultures such as Zoroastrianism also arose.

The cultures of the time did not evolve in isolation but were in frequent contact. The Amarna clay tablets show an active diplomatic exchange between Egypt and neighbors Canaan and Amurru in the Levant. The Mari archive of clay tablets also proves that active trade and contacts were established between Mesopotamian kingdoms and the Mediterranean areas further west. The Ugaritic texts show a network of trade and diplomatic correspondence between dignitaries across the Eastern Mediterranean and Mesopotamia. Egyptian hieroglyphs depict instances of diplomatic visits to the Pharaohs by Minoan and Mycenaean delegations. Economic relationships are apparent from archaeological finds of, for instance, lapis lazuli only available in modern-day Afghanistan, in burials in Egypt, or in Mycenaean-style swords found in Hittite locales. Most importantly, using bronze to manufacture artistic, religious, or military artifacts required access to copper, abundant in Cyprus and more extensively present further east into Mesopotamia.

These trading and diplomatic exchanges did not preclude violent confrontations between the major powers of the era. The Mycenaeans invaded and took over Crete around the middle of the second millennium BCE and confronted the Hittites in a series of conflicts that could have inspired the Trojan War of the Illiad. The Hittites projected power into Mesopotamia, facing off against several kingdom confederacies west of Assyria, burning Babylon, and maybe fighting naval engagements against Cyprus. Egyptian tomb hieroglyphs record notable conflicts, such as the battle of Meggido in 1479 BCE, between Thutmose III and the Canaanites, and the battle of Kadesh, close to the current northern Syria-Lebanon border, between Ramesses II and the Hittite Emperor Muwattalli II, in 1274 BCE.

As mentioned, the vibrant Late Bronze Age came to a shuddering halt in a civilization's collapse. Most of the leading civilizations had disappeared within a few hundred years, except Egypt. The Hittite Empire remained only a reference in ancient texts until the city of Hatusa was re-discovered in the 19th century. The Mycenaean kingdom-states vanished, the Assyrian Empire declined temporarily,

and Babylon lost all independence from the latter. After several hundred years of a dark age, the region moved into the Iron Age, with the emergence of the city-states of classical Greece and the Neo-Assyrian and Persian empires further east. The kingdoms of Judeah and Samaria appeared in the power vacuum created in the Levant from the collapse of Hatti, Assyria, and the retrenchment of Egypt. What was the cause of this collapse? A combination of mass migration and invasions from the western and central Mediterranean, coupled with severe droughts and other natural disasters, proved to be disruptive enough to take down whole empires. It remains a hotly debated issue in the historical discipline, centered more on the relative merits of specific causes and how they interacted rather than the broad outlines of what transpired.

The archeological record suggests that over a few decades, numerous locales in the Eastern Mediterranean, in what is now Syria, Lebanon, Jordan, and Israel, were destroyed in fiery conflagrations. This has been attributed partially to waves of invasions or migration from the so-called Sea Peoples[11] traveling by sea and land. They could have entered areas already depopulated for other reasons or destroyed them as they entered the region. The primary record of their existence can be found in Egyptian hieroglyphs, depicting the successful repulse of their invasion by Pharaoh Ramesses III. The name given to these groups in ancient texts has been sometimes interpreted as identifying either their origins (such as the Sherden originating maybe from Sardinia) or their descendence (such as the Peleset foreshadowing the Philistine or the Palestine peoples).

Evidence shows that climate events might have caused these massive and disruptive migrations. A significant drought affected the Mycenaean city-kingdoms, bringing about their demise.[12] Moreover, it has also been argued that droughts affected Central Europe and Northern Italy, thus leading to a mass migration towards the east and south of more than a hundred thousand people.[13] Severe climate events seem also to have contributed directly to the demise of the Hittite Empire. Although the record shows they were well used to managing the vagaries of climate fluctuations, around 1200 BCE, a multi-year drought devastated the region. The evidence for this comes from the examination of tree rings. These show a multidecade spell

11. See Sanders and others (1985).
12. See Carpenter (1966).
13. See Kristiansen (2018).

of dry weather, which also coincides with more frequent mentions of famines and grain scarcity.[14]

2.2 Climate Events and the Eastern Mediterranean Collapse (circa 1000 ACE)

Over the millennia, the Nile River has provided a key source of sustenance to the inhabitants of Egypt, which would otherwise be surrounded by barren deserts and the seas. The regular annual floods of the Nile valley, created as Indian Ocean monsoons enter inland south in Africa, increase the volume of the river, which, as it subsides back, leaves a rich soil where different seeds can be sown. The extent of grain production in the Nile River could reach enough volumes to be stored prudentially or even exported to neighboring areas around the Mediterranean and into the Levant.

Hundreds of miles to the northeast of the Nile Delta, the steppes across the Amu Darya River (currently a part of the border between Turkmenistan, Afghanistan, Uzbekistan, and into Tajikistan, an area known historically as Transoxiana from the river's Latin name Oxus) were home to nomadic and pastoralist Turkic tribes. These tribes depended on the annual migration pattern between winter grounds and more fertile areas.

Significant climate dislocations dramatically altered both areas at the turn of the first millennia. On the one hand, although the Nile River was subject to drought spells of about one drought year every half-century through the six centuries before 900 ACE, around the close of the first millennium, nine episodes of drought, totaling twenty-six years, hit the valley over a period lasting more than a century. It represented a tenfold increase in the frequency of droughts compared to the previous six centuries. As noted in the previous case study, ancient civilizations were able and prepared to withstand regular periods of drought, planning accordingly during the years of abundance. However, the institutional and administrative underpinnings were not generally prepared to deal with periods of food scarcity lasting more than two years.

On the other hand, and at a similar time, a cold weather anomaly hit the steppes, dislocating the seasonal migration pattern of the pastoralist Turkic tribes. Cold anomalies had been recorded before, but as Transoxania and Mesopotamia were affected now at the same

14. See Manning and others (2023).

time as Egypt ceased to provide a buffer of grain supply due to the droughts, calamitous famines spread across the whole region including Mesopotamia and Syria.[15] As the level of the Nile dropped to shallow levels between 1000 and 1100, the population of Egypt collapsed. While in the centuries, between 700 ACE and 900 ACE, its population hovered around 2.5 million, it dropped to 1.6 million around 1000 ACE.[16]

The economic effects of the climate shocks experienced from Egypt to Mesopotamia and Iran are apparent in modern statistical compendiums. According to the Maddison historical database,[17] GDP per capita in Egypt in 1000 ACE was 18 percent below 730 ACE, and by 1120 ACE was still ten percent below the level three centuries before. In Iraq (that is, Baghdad), income per capita in 1120 ACE was 17 percent below the level observed 120 years before, while in Turkey, it had fallen 3 percent over the same period. These magnitudes are even more dramatic if one assesses the gap between workers' incomes and the subsistence level of wages. The historical record shows that the daily wage for unskilled urban workers in Cairo and Baghdad fell from three to four times the subsistence level for a family of four by 800–900 ACE to two times in Baghdad and one and a half times in Cairo by 1100 ACE.[18]

After the burst of conquests, the Muslim world in the Eastern Mediterranean was organized as independent regional powers or dynasties, such as the Fatimid Caliphate in Egypt, the Buyid Emirates in Mesopotamia and Persia, and the Samanid Amirates further east towards Transoxania. Bordering them in Asia Minor was the remainder of the Byzantine Empire that had withstood the initial Arab Muslim advances. The economic effects that resulted from the climate events described were also the result of amplifications stemming as institutions of government felt the pressure of restive and hungry populations, collapsing tax revenue, and internecine violence, including anti-Christian as well as Sunni-Shia riots. Land taxation in Egypt fell by a third between the late 9th and the late 11th centuries,[19] where riots spread to the unpaid soldierly. Bedouin raids compounded the chaos in Egypt, and the Fatimid dynasty resorted to price controls and the seizure of all the grain traversing the Nile.

Further east, the cold anomalies started to generate sizeable Turkic migration waves, which came to be grouped under the

15. See Ellenblum (2012).
16. See Russell (1966).
17. See Bolt and Van Zanden (2020).
18. See Pamuk and Shatzmiller (2014).
19. See Russell (1966).

denomination of Seljuk Turks. In their southwesterly advance, Iran collapsed, and Baghdad fell into civil war. The Seljuk Empire ended the centuries-old dominance of the Arab Muslim dynasties from the Levant eastward. As they pushed into Asia Minor, heavy pressure came to bear on the Byzantine Empire and the Christian Kingdom of Georgia. The alterations these events provoked for Christian pilgrimages to Jerusalem, alongside the calls from Byzantine Emperor Alexios I Komnenos for military assistance, were crucial ingredients for the First Crusade in the late 11th century.

2.3 The Bhola Cyclone, the Indo-Pakistani War of 1971, and the Creation of Bangladesh

The end of the British Raj in 1947 was a tumultuous and violent episode. The promises of independence from the British Empire, exhaustion from the Global War in Europe and Asia, both in the subcontinent and in the United Kingdom, local rebellions, and ethnic and religious tensions all came together and resulted in the division of the Raj among roughly religious lines. This division came through as a turbulent political solution to a tough three-side negotiation between the United Kingdom, which looked to extricate itself from colonial oversight, the Indian National Congress party, which had been advocating since the late 19th century for independence, and the Muslim League, that had been formed early in the 20th century to secure political representation for Muslims in the Raj. The tensions between these three leading players were accelerated by ethnic violence between Muslims and Hindus as the date of independence approached, particularly in mixed communities. The resulting violent partition saw the creation of two different countries. On the one hand is India and on the other is Pakistan, formed by West and East Pakistan (today's Bangladesh). Pakistan was then originally separated geographically by more than a thousand kilometers. During the partition, millions died and millions migrated.[20]

The relations between India and Pakistan remained tense and resulted in several border conflicts, some of which are still latent such as in Kashmir. The nature of these tensions was and remains multifaceted, ranging from border disputes, geopolitical proxy associations with the U.S., and the U.S.R.R. during the Cold War, and

20. See Bharadwaj and others (2008).

contrasting approaches and conflicts with China. The division of the Raj had split the Bengali region among religious lines between India and East Pakistan, a split that also harked back to British rule.[21] During the 1960s, these were compounded by ethnic and political divisions within Pakistan. The center of power in Pakistan resided in its Western part, although East Pakistan represented a larger share of the population. This disparate division of political power was further exacerbated by ethnic divisions, as West Pakistani citizens are of Punjabi and Pashtu descent, while East Pakistanis were mostly Bengalis.

After independence, Pakistani institutions were weak, as the country saw a sequence of military coups. This further impaired the possibility of appropriate representation in a country sharply divided by ethnicity and geography. By 1960, demands for higher degrees of Bengali autonomy within Pakistan gathered steam, mainly through the Awami League led by Sheikh Mujibur Rahman. Its main political planks were the recognition of the Bengali language and the push for a much looser Federal organization of Pakistan. Social turmoil in the last part of the decade led to a military government takeover led by the Commander in Chief of the Army, Yahya Khan, who both suspended the Pakistani constitution and also created the conditions for the first-ever elections in all of Pakistan, as a way to defuse internal turmoil. They were scheduled to be held in late 1970.

Into this cauldron of political and ethnic tensions came a natural disaster of historic proportions. The (former) East Pakistani coastline corresponded to the Indian Ocean part denominated the Bay of Bengal. The agricultural activities therein benefit from the fact that the area of modern Bangladesh corresponds to the drainage basin of large rivers, forming the Ganges Delta. It is a low-lying area with an average height of just a few tens of meters above sea level. Tropical cyclones form in the Bay of Bengal several times a year, contributing to the monsoon rains that provide critical support for the agricultural areas surrounding the bay. As in many other South and East Asian areas that share these characteristics, high population density can be supported by and contributes to agricultural activities that are water intensive.

21. See Kalyanaraman (2022).

The 1970 monsoon season, however, was extreme. In November, the Bhola Cyclone, probably the deadliest in modern records, reached wind speeds of nearly 200 km/h. It made landfall in the Ganges Delta, killing hundreds of thousands of people. The whole area was devastated mostly due to tidal waves that ravaged towns and crops. The magnitude of the disaster in East Pakistan, part of a country with weak institutions, was compounded by ineffective support from the central government. On the one hand, the geographical distance between the affected areas and the centers of administrative and political power thousands of kilometers away likely contributed to the lackluster government response. On the other hand, some views indicate that extant political divisions created little incentive for the West Pakistani leadership under Yahya Khan to assist.[22]

In any case, the resulting political backlash was brutal. In the elections a month later, the Awami League secured most seats in the National Assembly, all from East Pakistani constituencies. In contrast, the Pakistan People's Party gained the second most extensive set of seats from West Pakistan. As these results implied that the independence-minded Awami League would have control of the new government, an immediate political crisis occurred. Yahya Khan postponed the National Assembly's inauguration and attempted to mediate between the Pakistan People's Party and the Awami League, but talks floundered. Unrest spread through East Pakistan, and the conflict reached a tipping point in March 1971 when the government decided to crack down on East Pakistani independent and nationalist movements. It has also been pointed out that political dynamics were well on the way to pushing East Pakistan into independence, even without the repression and violence that followed the elections.[23] The resulting civil-war conditions created acute internal strife, as the East Pakistani military split along ethnic lines, forming nationalist paramilitary groups such as the Mukti Bahini. Millions of refugees fled across the border to India, joining an already large diaspora from the previous year's exodus from the immediate dislocations created by the cyclone. Moreover, from bases across the border, the Mukti Bahini continued operations into East Pakistan, and an independent Bangladeshi government was established.

22. See Miklian (2022).
23. See Rikhye (2020).

The intervention of India in the civil war responded to a multitude of reasons, both internal and external.[24] In practice, in late 1971 and within a few days, the East Pakistan military had been defeated, the civil war was over, and East Pakistan was on track to become independent Bangladesh.

2.4 Environmental Degradation, the Rwandan Genocide, and Conflict in the Congo Basin (1994–2001)

Between April and July 1994, hundreds of thousands of people, mainly of Tutsi ethnicity, were murdered in a genocidal rampage in Rwanda by Hutu gangs.[25] The specific and immediate trigger to this horrendous event was the death of Rwandan President Juvenal Habyarimana, a Hutu, as his plane exploded, apparently from a missile strike, killing also Burundi's President Cyprien Ntaryamira, who was Tutsi. Rwanda's Prime Minister Agathe Uwilingiyimana, a Hutu, was assassinated the next day. In the ensuing power vacuum, a Hutu extremist government took power in April 1994 in Rwanda, inciting and executing the genocide.

It has been noted that the deeper causes of the genocide lay in a complex interaction between environmental degradation, ethnic tensions, and weak institutions.[26] In Rwanda, one of the most densely populated countries in Africa, 96 percent of the population lived in the countryside, where 90 percent of the labor force was employed in agriculture. Unsustainable practices led to falling soil fertility, while degradation of watersheds and forest erosion resulted from overcultivation. This dwindling resource base resulted in increased stress between ethnic groups. In pre-colonial times, 'Tutsi' and 'Hutu' were fluid classifications based not on strict ethnic differentiation but rather on socioeconomic status and the positions within the economic system, mainly between pastoral (Tutsi) and agricultural (Hutu) activities. Colonial rule increased the rigidity of this classification as the Tutsi majority became associated with power and wealth, while the Hutu minority with subordination and toiling the fields. Rwandan independence resulted in the perception of a Hutu-dominated state apparatus.

24. See (Batabyal, 2020).

25. The exact number of victims of the genocide might never be known. The range of estimates is wide and has changed over time as well. See Guichaoua (2020).

26. See Diamond (2011), Percival and Homer-Dixon (1996).

In the early 1990s, several developments helped set the stage for the genocide.[27] As the exploitation of available land was reaching its natural limits, aggregate agricultural production fell 20 percent in per-capita terms between 1980 and 1990. A severe drought affected East Africa and Rwanda in particular, as rainfall totals fell 30 percent. The international prices of the cash crops—coffee and tea—exported by Rwanda collapsed at the time. Furthermore, from 1990 to 1992, the country was engulfed in civil war as the Rwandan Patriotic Front (RPF), predominantly made up of post-independence displaced Tutsi and their descendants, invaded Rwanda from their bases in Uganda, intending to topple the government. By July 1992, international pressure and governmental setbacks in the conflict allowed for a fragile agreement, signed in August 1993, between the RPF and Habyarimana's government. Tensions, however, lingered because of the existence of radical paramilitary groups associated with the Hutu state apparatus, the mainly Tutsi RPF, and the Rwandan army. The situation blew up into full-scale conflict and genocide less than a year later with Habyarimana's assassination.

The United Nations Security Council authorized in June 1994 a French-led military intervention, the "Operation Turquoise". Three thousand French and African troops entered Rwanda but were ineffective in stopping the genocide. As they left in August, the RPF took power, and shortly afterward, the genocide stopped.

The social and economic dislocations provoked by the genocide were enormous in Rwanda. As mentioned before, many hundreds of thousands of Rwandans died in the genocide (a significant fraction of the estimated Tutsi population). Per-capita output fell 36 percent in 1994, when the year before it had already fallen by 15 percent. Moreover, the end of the genocide and the collapse of Hutu rule did not stop regional violence. As the extremist Hutu government was falling under the pressure of the RPF, its cadres fled, alongside close to two million Rwandans of Hutu ethnicity, to neighboring Zaire. They took with them Central Bank reserves and established themselves in refugee camps right across the Rwandan border.[28]

The existence of those large refugee camps where the Hutu genocidaires escaped proved to be a thorn in the side of some members of the new national unity Rwandan government—particularly for General Paul Kagame, the head of the RPF and prominent Tutsi leader

27. See Richmond and Galgano (2019).
28. See Prunier (2008).

within the National Unity government. The institutional weakness of Zaire, where Mobutu Sese Seko played the refugee issue for domestic political goals, exacerbated the lingering tensions. In September 1996, General Kagame sent the Rwandan army across the border to deal with the alleged threat the militarized Hutu refugees posed. This invasion occurred in a regional situation where Zaire and its resources were perceived to be up for grabs. Eventually, Burundi, Uganda, and Angola, among others, also participated in the invasion. Hundreds of thousands of the Hutu refugees escaped West and Southwest through Zaire as the conflict flared up. Under the pressure of invasion and civil war, the Mobutu regime collapsed three years after the Rwandan genocide. Laurent Kabila became the leader of the newly denominated Democratic Republic of Congo (DRC), supported by the invading forces. War continued, however, and a fragile status quo was reached in the early 2000s.

The cost of the war in the DRC (formerly Zaire) was very high. Many of the thousands of Hutu refugees who escaped eventually returned to Rwanda. However, the United Nations Refugee Agency reckons that two hundred thousand refugees disappeared, likely perishing during the war. Other estimates point to a figure 50 percent higher.[29] The war left the most significant human toll since World War II, with over five million deaths, and GDP per capita in the DRC fell close to 40 percent between the years prior to the Rwandan genocide and 2001.

3. The Present: Quantitative Analysis

The previous section introduced the potential relationship between climate events and migration through the lens of the past by presenting four historical events. Now, in this section, we turn to a quantitative analysis to shed light on this relationship in the present. As an empirical approach, we propose a reduced-form specification that relates the emigration growth of a country with changes in climate-related variables as well as with the level of income per capita and population, and we estimate it by using panel data for 147 countries over the period 1990–2020. Then, in the next section, using the estimated model, we will try to give some insights into how migration pressures will change under different global warming scenarios.

29. See Prunier (2008).

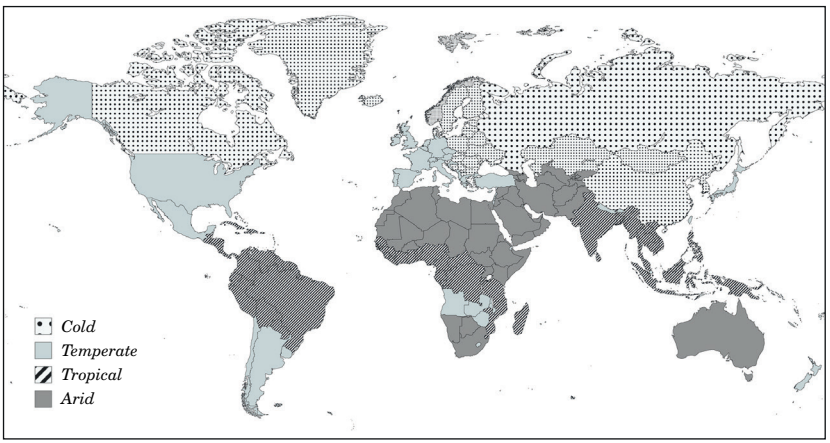
This section starts by describing the data construction and several sources from which we gathered information. Then, we explain the empirical approach used to account for the relationship between international migration and climate-related variables, and we end the section by presenting the results from the estimated model.

3.1 Data

3.1.1 Climate classification data

We've employed the latest Koppen climate classification information, revised by Peel and others (2007), to assign each nation a categorization encompassing most of its land. Our approach employs a more comprehensive classification system involving four categories: tropical, temperate, arid, and cold. Please refer to Figure 1 for a graphical depiction of this classification.

Figure 1. Climate Classification by Country



Source: Authors' calculations.
Notes: The estimation for each country is defined as the climate classification for the main covering area—see Peel and others (2007) for more detail. The figure shows the more general classification: tropical, temperate, cold, and arid.

3.1.2 Migration data

To gain insights into global migration patterns, we rely on census data from the Department of Economic and Social Affairs and Population Division (UNDESA) at the United Nations. This comprehensive dataset covers 1990 to 2020, with a five-year intervals, and offers a bilateral accounting of migration stocks between countries. It shows the foreign population residing in each country and their respective countries of origin. Thus, we can create a variable that reflects the number of individuals living abroad based on their birth country.

3.1.3 Agricultural data

The Crop and Livestock Production and Utilization data from the FAO's data collection registers the total value for producing different farming goods by country. This data helps us identify the countries that farm maize. Additionally, we use information from the Land & Water section of FAO's database to determine the duration of the growing season of maize and the month when it begins for different climate classifications. By utilizing the classification in Peel and others (2007), we can build a variable containing the months maize grows for each country.

3.1.4 Weather data

The Climate Change Knowledge Portal, hosted by the World Bank, houses valuable data covering most landmasses (excluding Antarctica) on a 0.5° latitude by 0.5° longitude grid. This information is gathered by interpolating monthly climate anomalies observed at weather stations. We rely on the extensive long-term time series (1901–2020) featuring monthly data by country. Additional details can be found in Harris and others (2020).

3.1.5 Economic data

We rely on the World Development Indicators provided by the World Bank, which comprises a time series of various economic variables for each country. Among these variables, we primarily use each country's total population data and the GDP per capita (purchasing power parity, PPP) in 2017 U.S. dollars.

3.1.6 Weather projections

We utilized data from the Climate Change Knowledge Portal[30] for various scenarios outlined in Table 1.

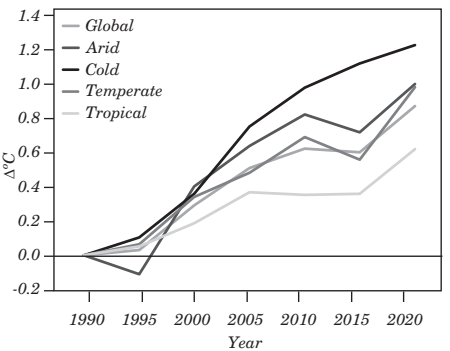
3.1.7 Projected population

We have utilized the data provided on the *AR6 Scenario Explorer* website, hosted by the International Institute for Applied Systems Analysis (IIASA). Specifically, we have used version 1.1 of the country-level estimates generated by the IIASAPOP 2.0 model. The model's output has been estimated for different SSP scenarios and their experimental variations.

3.2 Trends over Time

Despite a brief estimation period, we find a significant and steady rise in temperature. By 2020, the world's mean temperature had risen by 4 percent relative to the benchmark of 1990 (0.8°C). It is worth mentioning that those nations deemed 'cold' experienced the highest rise in temperature, with nearly 8 percent compared to 1990, while tropical nations had the smallest rise at just under 2.5 percent compared to 1990 (Figure 2).

Figure 2. Cumulative Growth Rate of the Average Temperature for the Growing Season of Maize with Respect to 1990



Source: Authors' calculations.
Notes: Cold areas show the highest increase in temperature, while tropical areas show the lowest increase in temperature.

30. See Harris and others (2020).

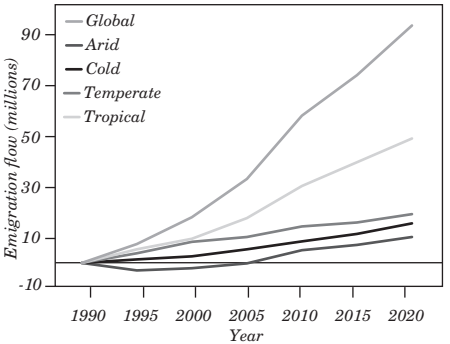
Table 1. Description of the Scenarios used for Projections

Scenario	*Description*	*Warming range by 2100*
SSP1-2.6	Scenario that supports increasing sustainability with global emissions cut severely but reaching net zero after 2050.	1.3°C - 2.4°C
SSP2-4.5	Presents a 'middle of the road' scenario in which emissions remain around current levels before starting to fall around mid-century but do not reach net zero by 2100.	2.1°C - 3.5°C
SSP3-7.0	Presents a pathway in which countries are increasingly competitive, and emissions continue to climb, roughly doubling from current levels by 2100.	2.8°C - 4.6°C
SSP5-8.5	Presents a future based on an intensified exploitation of fossil fuel resources where global markets are increasingly integrated, leading to innovations and technological progress.	3.3°C - 5.7°C

Source: Authors' calculations.

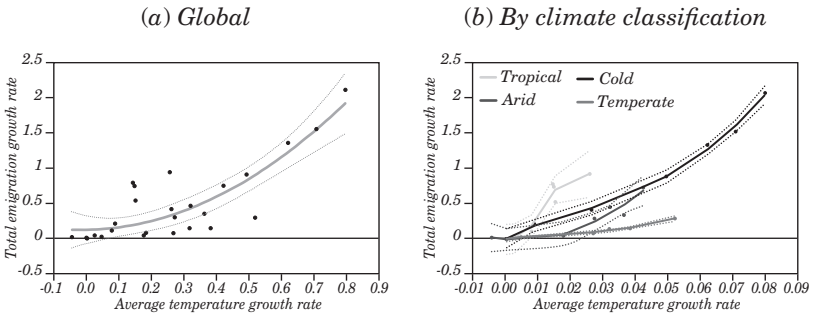
Along with the rising temperatures, emigration has also significantly increased—meaning the number of individuals residing in a country other than their homeland. In 2020, there was a global cumulative increase in emigration of nearly 150 percent. The countries with colder climates experienced the most significant increase, with an almost 250 percent rise, while temperate countries had a more modest increase, less than doubling their emigration stock by 2020. However, it is worth noting that tropical countries have also seen a substantial increase in emigration, with the second-highest growth rate for most of the period examined. The number of people emigrating from tropical countries has tripled by 2020 (Figure 3).

Figure 3. Cumulative Growth Rate of the Emigration Stock with Respect to 1990



Source: Authors' calculations.
Notes: Cold areas show the highest increase in emigration, while temperate areas show the lowest increase in emigration.

Figure 4. Relationship between Temperature and Emigration



Source: Authors' calculations.
Notes: The scatter plot is constructed by using the average of the emigration and temperature growth rate by year and climate.

Careful analysis of the relationship between emigration and temperature rise during the studied period is vital. Notably, data reveals a significant surge in emigration as temperature continues to climb, highlighting a positive and nonlinear correlation between the two factors. This indicates that emigration is particularly sensitive to significant temperature spikes, as depicted in Figure 4a.

It is worth noting that there is a significant variation in the relationship between climate type and emigration. Countries with

tropical climates are more susceptible to temperature fluctuations, resulting in a significant increase in emigration despite experiencing the slightest temperature increase among the countries studied, as shown in Figure 4b.

3.3 Empirical Approach

To account for the relation between international migration and climate-related variables, similar to Missirian and Schlenker (2017), we propose a reduced-form model that relates a migration measure with temperature and precipitation. In the same spirit, we estimate such a model by using panel data with country- and time-fixed effects, which allows us to control for any time-invariant unobservable that affects migration decisions and correlates with the climate variables.[31]

However, we extend the approach developed by Missirian and Schlenker (2017) in at least three ways. First, instead of using asylum applications of non-OECD countries to the European Union, we use census emigration data available in UNDESA –which considers migration from all countries toward the rest of the world–, which allows us to construct the total emigration stock for each country of origin in the world and also grants us more geographical variation to inform the regression. This extension will also be important for the next section, where we will use the estimated model to project emigration under several possible future climate scenarios. Because we are taking into account the total emigration stock for all the countries in the world, the estimated model will allow us to project the total emigration for each country of origin to the rest of the world rather than towards a particular region. Second, Missirian and Schlenker (2017) work with data between 2000 and 2014, while we are taking advantage of the fact that UNDESA data is available between the years 1990 and 2020 at a five-year frequency, which allows us to capture a larger time variation of the global warming process. Third, and most importantly, we include GDP per capita as an additional explanatory variable. The income level is potentially a driver of emigration, warranting its inclusion in the empirical estimates, as highlighted in Rikani and others (2022).

However, we posit that the interaction of GDP per capita with changes in the climate variables is also a potentially important determinant of migration. The development level influences countries'

31. For example, the geographical location could correlate with both climate variables and the costs of emigrating.

ability to adapt to climate change, an ability that we expect to increase with the country's income level.

Formally, to link the growth in the total emigration stock to climate variables in the source country, we estimate the following fixed-effect regression model:

$$E_{it} = (\beta_1 + \beta_2 y_{it})\, T_{it} + (\beta_3 + \beta_4 y_{it})\, T_{it}^2 + \beta_5 y_{it} + \theta\, Pop_{it} + \alpha_i + \gamma_t + \varepsilon_{it}, \qquad (1)$$

where E_{it} is the ratio between the emigration stock from country i in year t with respect to the emigration stock from the same source country in the year 1990. T_{it} corresponds to the mean temperature of the maize growth season of country i over a five-year period where the last year is t. y_{it} corresponds the log of the GDP per capita of country i in year t. Pop_{it} is the ratio between the population of country i in year t with respect to its population in 1990. α_i and γ_t are the country and year fixed effects, respectively. Finally, ε_{it} is the error term.

3.3.1 Results

Table 2 presents the OLS estimation for four alternative specifications, which differ in whether we include precipitation on top of temperature as weather variables and the inclusion of the log of the GDP per capita interacting with them. All specifications are estimated with robust standard errors.

Column (1) corresponds to the closest model to the one estimated by Missirian and Schlenker (2017). Here, we regress the ratio of emigration stock on linear and quadratic terms for temperature and we control for population growth and for country- and time-fixed effects. The results, in line with Missirian and Schlenker (2017), show a negative coefficient for the linear term and a positive coefficient for the quadratic term. These results imply a nonlinear relationship between emigration growth and temperature changes, with both negative and positive deviations from an optimal temperature leading to an increase in emigration. In particular, the optimal world average temperature under this specification is 20.7°C. Column (2) adds precipitations as an additional weather variable to the previous specification, but the resulting estimated coefficients are not significant.

The model in Column (3) extends the model from Column (1) by including the log of GDP per capita interacting with the linear and quadratic terms of temperature. The estimated coefficients for these

new interactions are positive for the linear relationship and negative for the quadratic one. This implies that the initial positive quadratic effect of temperature is dampened for richer countries.

One plausible explanation for this result is that higher-income countries are more capable of implementing adaptation policies because they have the resources or the ability to borrow abroad to fund the substantial investment projects required to ameliorate the damages from droughts and floods.

Table 2. Baseline Regression

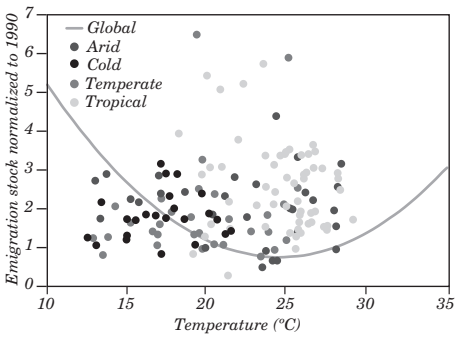
	(1)	*(2)*	*(3)*	*(4)*
	Only temperature	*Temperature and rain*	*Baseline*	*Baseline with rain*
Population norm. to 1990	-0.117	-0.139	0.009	0.034
	(0.13)	(0.14)	(0.07)	(0.07)
5-year average temperature	-1.626**	-1.662**	-5.084**	-5.092**
	(0.58)	(0.59)	(1.83)	(1.91)
5-year average temperature squared	0.039**	0.039**	0.137**	0.135**
	(0.01)	(0.01)	(0.05)	(0.05)
5-year average total precipitation		-0.005		-0.021
		(0.00)		(0.01)
5-year average total precipitation squared		0.000		0.000*
		(0.00)		(0.00)
Log GDP pc (PPP, USD 2017)			-3.929*	-4.091*
			(1.59)	(1.65)
Temperature and GDP linear interaction			0.435*	0.426*
			(0.17)	(0.18)
Temperature and GDP quadratic interaction			-0.012**	-0.012*
			(0.00)	(0.00)

Table 2. Baseline Regression (continued)

	(1)	*(2)*	*(3)*	*(4)*
	Only temperature	*Temperature and rain*	*Baseline*	*Baseline with rain*
Rain and GDP linear interaction				0.002*
				(0.00)
Rain and GDP quadratic interaction				-0.000*
				(0.00)
Opt. Temp.	20.7	21.1	24.5	24.5
N countries	154	154	147	147
N years	7	7	7	7

Source: Authors' calculations.
Notes: Standard errors in parentheses. Weather variables are estimated for the growing season of maize. * $p < 0.1$, ** $p < 0.01$, *** $p < 0.001$.

Figure 5. Relationship between the Average Temperature for the Growing Season of Maize and the Ratio between the Emigration Stock in 2020 and 1990



Source: Authors' calculations.
Notes: The line shows the estimated function of this relationship by our baseline specification, using the average value for population and GDP per capita. Countries are shown by their climate classification.

Finally, Column (4) adds precipitations to the specification from the previous model. The effects of their interactions are small. Therefore, our preferred model is the one from Column (3), and this is the baseline model we will use for the analysis performed in the following sections.

We end this section by presenting in Figure 5 the quadratic response of the emigration growth between 1990 and 2020 as a function of the world average temperature using the estimated model from Column (1) in Table 2. We can observe that the optimal temperature is 24.5°C—positive and negative deviations from this threshold increase emigration. In the figure, we also add the emigration growth rate for the countries included in the sample and we classify them by their type of climate (i.e., tropical, cold, arid, temperate). Most tropical countries exhibit average temperatures that are located in the right part of the quadratic response, which means that a positive change in temperature leads to an increase in emigration. In contrast, countries classified with temperate and cold climates are located in the left part of the quadratic response, which implies that an increase in temperature decreases emigration abroad for such countries. This result suggests that the effects of global warming will be heterogeneous over types of climate. The nonlinear response implies that warmer countries will be the most negatively affected, while cold countries may benefit within a certain range of temperature increases.

3.4 Heterogeneity of the Impacts by Type of Climate and Income per Capita

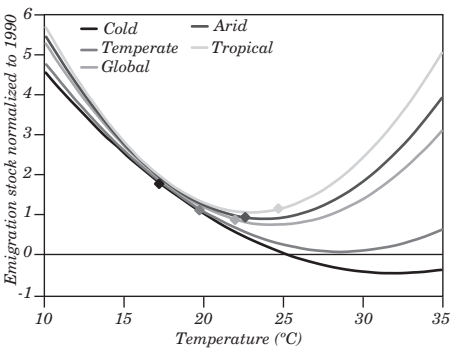
In this section, to shed more light on the heterogeneity of the effects, we dive deeper into how the type of climate and income per capita of countries shape their nonlinear relationship between emigration and temperature.

Figure 6 uses the estimated baseline model—column (3) in Table 1—to compute the quadratic response of the countries grouped in the four types of climate, which differ in their GDP per capita. In 2020, the average GDP per capita of tropical countries was USD 9,381.4; for temperate countries, USD 31,315.2; for arid countries, USD 17,294.0; and for cold countries, USD 30,945.0. Because the quadratic positive relationship of temperature and emigration is diminished as GDP per capita increases, tropical countries with a lower income level are less resilient to global warming, exhibiting an upward and strongly increasing relationship for a temperature higher than 23°C. In contrast, cold countries, which are on average much richer, exhibit a negative relationship for any level of temperature below 32°C. A plausible explanation for these results is that the capability of countries to adapt to climate change relates to their income level. By investing more in adaptation, richer countries ameliorate the negative

impacts of climate change on productivity, wages, and probability of conflict, thus reducing the pressures for emigration.[32] Figure A.1. in the Appendix presents the baseline model for each type of climate, including the confidence intervals for the estimated quadratic response functions.

However, there is a second source of heterogeneity besides the income per capita of countries: the average temperature. Figure 6 also shows in diamonds the average temperature for each one of the four types of climate. The average temperature between 2015 and 2020 for tropical countries is 24.5°C; for arid countries, 23°C; for temperate countries, 20°C; and for cold countries, 17°C. For a given GDP per capita, tropical countries with higher average temperatures will be located more to the right part of the quadratic response function, meaning they will face a larger increase in emigration for the same marginal increase in temperature than countries belonging to colder climates.

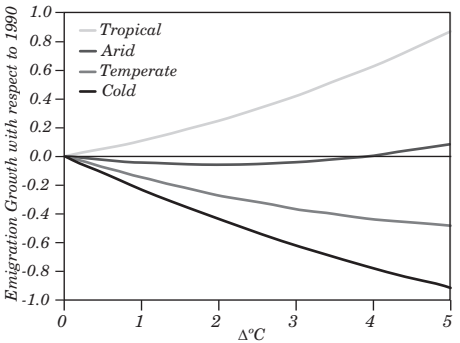
Figure 6. Relationship between the Average Temperature for the Growing Season of Maize and the Ratio between the Emigration Stock in 2020 and 1990 by Climate Classification



Source: Authors' calculations.
Notes: The lines show the estimated function of this relationship by our baseline specification for different climates. The dots represent the average temperature in 2020 for each climate.

32. See Carleton and Hsiang (2016).

Figure 7. Estimated Growth in Emigration for Temperature Increases of up to 5°C for the Average Temperature for 2020 by Climate Classification



Source: Authors' calculations.

Figure 7 presents the quadratic response functions for each type of climate for increases up to 5°C starting from their average temperature over the 2015–2020 period. Here, we can see in detail the different responses to temperature increases arising from a combination of different levels of GDP per capita and different current temperatures for each type of climate. For tropical countries, a rise of 2°C is projected to increase the total number of emigrants by 50 percent, while a rise of 4°C would almost double the current stock of emigrants.[33] If we consider that the total stock of emigrants from tropical countries in 2020 is 85 million people, then under the scenario of a 4°C increase, we would expect 53 million more displaced people from tropical countries (138 million in total, a 62 percent increase) due only to climate-related causes. For countries with temperate and cold climates, a decline in the number of emigrants is expected. This result is in line with the findings from previous literature, and it can be rationalized by the increase in labor and agricultural productivity.[34]

33. The emigration ratio with respect to 1900 is rescaled to express the increases with respect to the emigration stock in 2020.

34. See Cruz and Rossi-Hansberg (2022).

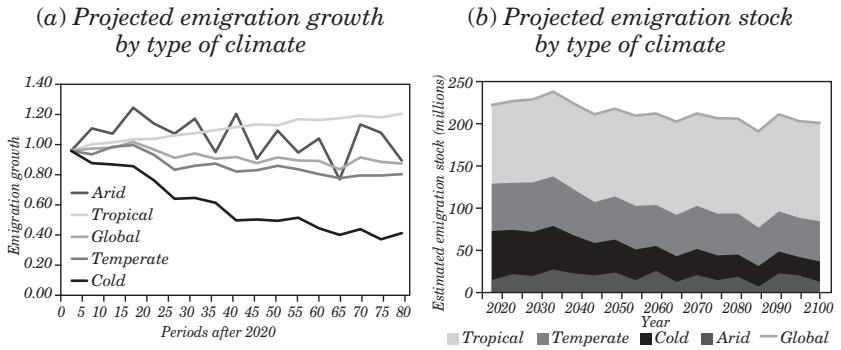
4. The Future: Projecting Climate Scenarios up to 2100

4.1 IPCC Scenarios

In the previous section, we performed an empirical analysis to shed light on the present relationship between climate change and emigration using data from the last 30 years. Using the estimated baseline model in Table 1, we turn the analysis now to project emigration pressures for a selected group of possible future climate change scenarios over a time horizon ranging up to 2100. We use the Shared Socioeconomic Pathways (SSPs)[35] developed by the Intergovernmental Panel on Climate Change (IPCC) for this exercise. In particular, we choose the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP4-8.5 scenarios. As explained in Section 3, the estimated global warming of each of these four scenarios by 2100 is 1.8°C, 2.7°C, 3.6°C, and 4.4°C, respectively.

To perform the projections, we feed the estimated baseline model with disaggregated temperature data from the IPCC projected scenarios at country level for the period 2020–2100. To assess the pure effect coming from global warming, we keep the GDP per capita constant at their 2020 level.[36] This simplification poses a caveat.

Figure 8. Projections Based on the SSP2-4.5 Scenario



Source: Authors' calculations.

35. The Shared Socioeconomic Pathways (SSPs) are climate change scenarios of projected socioeconomic global changes up to 2100, as defined in the IPCC Sixth Assessment Report on climate change in 2021. They are used to derive greenhouse gas emissions scenarios with different climate policies.

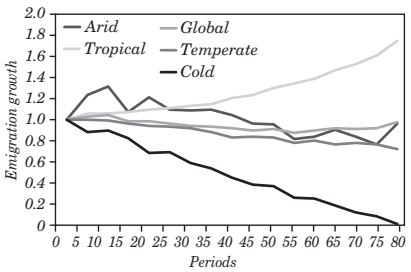
36. For this exercise, the population varies according to the projected growth rate for each country.

We are not taking into account that the possible positive income growth of countries might help them to adapt and become more resilient to temperature increases. However, we do this because we are also uncertain about how climate change will affect future GDP growth rates at country level, which can be negative.

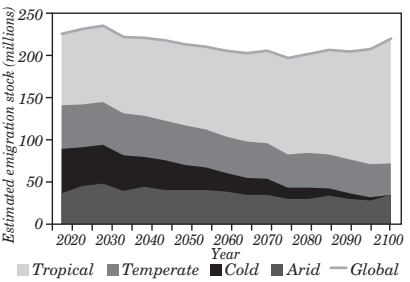
Figure 8 presents the results for the SSP2-4.5 scenario. Projections are shown grouping countries by type of climate. Panel (a) shows the growth of emigration with respect to the stock in 2020. In this optimistic scenario, we can observe that the tropical countries will still face emigration pressures, increasing 20 percent their emigration stock. In panel (b), which shows the dynamics in terms of stock, the number of people from tropical countries living abroad is projected to increase from 90 million in 2020 to 108 million in 2100. The opposite happens in cold and temperate countries, where emigration decreases at about 60 percent and 20 percent, respectively. Two forces drive this decline. First, the number of people emigrating abroad is reduced, and second and most importantly, people who are originally from cold and temperate countries and were living in countries with other climates (e.g., tropical) return to their countries of origin with cold and temperate climates. Such change in composition can be better understood in panel (b), where the stock of emigrants from cold and temperate countries is drastically reduced.

Figure 9. Projections Based on the SSP2-4.5 Scenario

(a) Projected emigration growth by type of climate



(b) Projected emigration stock by type of climate



Source: Authors' calculations.

Similarly, Figure 9 presents the results for the SSP5-8.5 scenario. The projected emigration dynamics in SSP1-2.6 become stronger for the SSP5-8.5 scenario with a higher average world temperature increase. In this most extreme IPCC scenario, the projected emigration from tropical countries increases by 91 percent, i.e., goes from 90 million in 2020 to 172 million people in 2100. On the other hand, there will be almost no emigration left from cold and temperate countries by 2100. Scenarios SSP1-2.6 and SSP3-7.0 are presented in the Appendix in figures A.2. and A.3.

4.2 Tipping-Point Scenario — The AMOC Collapse

This scenario is characterized by the collapse of the Atlantic meridional overturning circulation (AMOC), which could have global ramifications, including abrupt cooling across large parts of the northern hemisphere, changes in tropical rainfall, and nonlinear changes in sea-level rise in the North Atlantic Ocean.

The North Atlantic thermohaline circulation is a linchpin in harmonizing temperature disparities between its realms and the equator. Operating on the premise of salinity-induced water movement, it serves as a conduit for heat transportation from equatorial zones to polar regions. An AMOC collapse is poised to disrupt this delicate balance, jolting tropic ocean temperatures while cooling northern seas. This ripple effect extends to surface temperatures, prognosticating a stark shift, such as a notable chill in northern Europe and North America. Therefore, if the AMOC collapses, not only would tropical regions face emigration pressures due to the increase in temperature as in the IPCC scenarios, but also cold and temperate countries would freeze, thus leading to an increase in the migratory outflows from these countries. Recent work underscores a steeper decline in AMOC than previously envisaged, nudging forward the potential collapse timeframe (now 2050 rather than post 2100).[37]

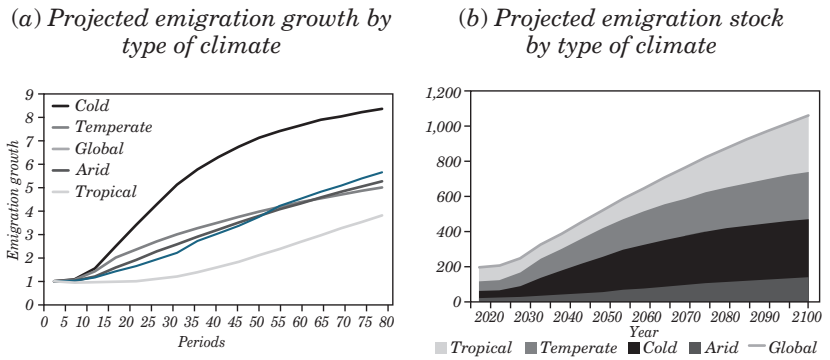
To assess the emigration impacts of the AMOC-collapse scenario, we rely on the results in temperature change projected by Orihuela-Pinto and others (2022) in the aftermath of an AMOC shutdown, and we feed our previously estimated model with such changes. The simulations from several climate models provided by Orihuela-Pinto and others (2022) are performed with high spatial resolution, much

37. For a more detailed explanation, see Ditlevsen and Ditlevsen (2023) and Orihuela-Pinto and others (2022).

more granular than the country-level data that we used to estimate our model. Thus, to be able to link the AMOC scenario data with our model, we adapt the data in a two-step procedure. First, given that there is no probability distribution associated with each model, we use just the simple average temperature change across the models as the temperature change to run the projections in our model. Second, we perform a search and matching algorithm to find the coordinates in the AMOC shutdown simulation data closest to each country's capital city.[38] This allows us to map surface temperature trajectories from the AMOC shutdown simulation data to each country in our sample over a period of 100 years after the AMOC shutdown.

Next, in a similar fashion, as we did to simulate the IPCC scenarios, we feed our estimated model with the temperature changes from the AMOC shutdown scenario. Figure 10 shows that, under the AMOC shutdown scenario, the total outward migration would increase significantly for countries across all the climates.

Figure 10. Projections Based on the AMOC-Collapse Scenario



Source: Authors' calculations.

38. We get the coordinates of each capital city in our sample from the Simplemaps: World Cities Database.

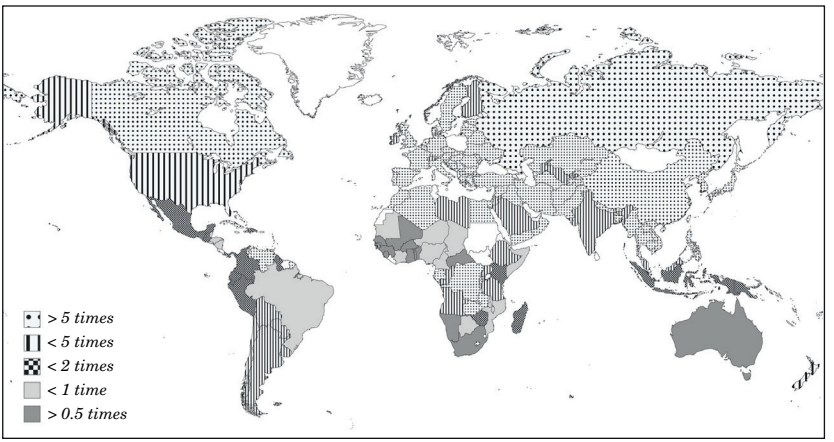
Panel (a) presents the growth of emigration with respect to the stock in 2020 for countries grouped in each climate following the AMOC shutdown that is assumed to happen in 2025. We can observe that the repercussions extend beyond tropical regions grappling with heightened temperatures, akin to IPCC scenarios. Now, cold and temperate countries face the brunt as the freeze prompts a surge in migratory outflows, followed by arid and tropical countries. In panel (b), which shows the emigration dynamics in terms of stock, the number of people from cold and temperate countries living abroad is projected to increase from 50 million in 2020 to 450 million in 2100, and from 50 million in 2020 to 250 million in 2100, respectively. The increase of people living in tropical countries goes from 90 million in 2020 to 125 million in 2100. The total number of people living in places other than their country of origin in the world is projected to increase from 200 million to more than 1 billion between 2020 and 2100.

Figure 11 shows the emigration growth projections disaggregated at country level. It is possible to observe that cold and temperate countries in North America, Europe, and South America, as well as Russia, India, and China, would be strongly affected if the AMOC shutdown occurs because these are the countries that would face larger temperature decreases leading to stronger emigration pressures.

5. Conclusions

In this paper, we have studed the emigration pressures associated with climate change and shed light on how it could evolve as the climate degrades further in the future. A key challenge to address this question is that the available data on migration goes a few decades back, which seems not to be a large enough time span to fully capture the potential highly nonlinear relationship between environmental degradation and migration. Recognizing this data limitation, we start the analysis with a narrative approach focusing on four historical case studies. Relying on noneconomic sources, we document that severe climate disruption has led to significant outward migration in the past, driven by social conflict and, in some cases, societal collapse.

Figure 11. Emigration Growth by Country for AMOC-Collapse Scenario



Source: Authors' research.

Then, we exploit the available international census data on migration stocks to perform a regression panel approach in order to estimate the present relationship between emigration and climate change. We find a nonlinear relationship between climate change and migration, with a U shape around a "temperature optimum." Nonlinearity is stronger in poorer countries due to limited adaptation.

To speak of future possible climate-related migration trajectories, using the estimated model, we project five different IPCC scenarios and a tipping-point scenario associated with the AMOC collapse. We find moderate effects on migration increase under moderate climate IPCC scenarios, but migration would double for tropical areas in the most extreme scenario. Regarding the AMOC-collapse scenario, the total emigration in the world would increase from 200 million in 2020 to 1 billion in 2100, mostly driven by the increasing emigration from cold and temperate countries.

This result differs from the projected IPCC scenarios, in which emigration pressures arise mostly in tropical countries. We interpret our results as a lower bound of the possible effects, given (i) the non-well-captured nonlinearities and (ii) the potential fall in income due to climate damages that limit adaptation.

The challenges posed by climate change are multidimensional. In this paper, we have focused on the specific issue of migration driven by climate. The interaction of these migration flows with societal tensions and conflict is apparent from the historical record, and its empirical relevance from a contemporaneous perspective is left for future work. As highlighted in our work, understanding the effects of climate change in societies requires a multidisciplinary approach, both to inform the empirical strategy as well as to devise potential policy interventions to mitigate its effects.

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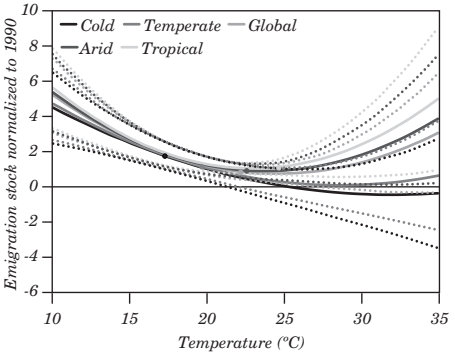
Appendix

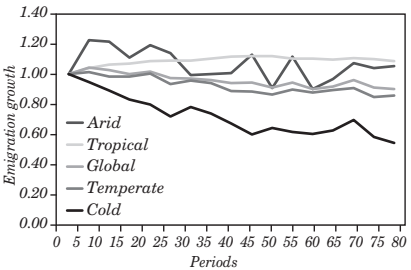
Figure A1. Relationship between the Average Temperature for the Growing Season of Maize and the Ratio between the Emigration Stock in 2020 and 1990 by Climate Classification



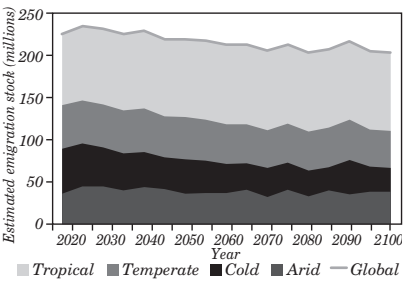
Source: Authors' calculations.
Notes: The lines show the estimated function of this relationship by our baseline specification for different climates. Confidence intervals at 90 percent.

Figure A2. Projections Based on the SSP1-2.6 Scenario

(a) Projected emigration growth by type of climate



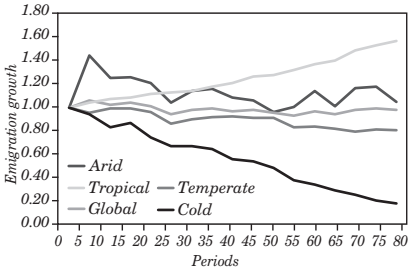
(b) Projected emigration stock by type of climate



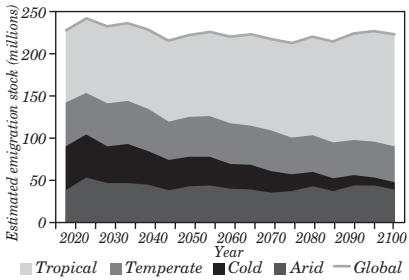
Source: Authors' calculations.

Figure A3. Projections Based on the SSP3-7.0 Scenario

(a) Projected emigration growth by type of climate



(b) Projected emigration stock by type of climate



Source: Authors' calculations.

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