Navigating Climate Economics: Perspectives for a Sustainable Future

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Contents

Introduction

Climate Change & Environmental Impacts

Climate Change Adaptation & Mitigation Strategies

Technological & Economic Assessments

Specific National/Regional Policy Assessments

Foreword by Andrew Leach

Climate change is the most pressing environmental policy issue of our time, and one of our most pressing economic policy challenges. It's a challenge because of its global nature, but also because of the timing of the costs of benefits of policy interventions. Climate change policies, at their most basic level, are asking people alive today to make sacrifices that will largely benefit the youngest among us today and those not yet born. The geographic and temporal separation between costs and benefits of action on climate change makes it challenge unlike any other environmental policy problem we have faced as a society. This book presents an opportunity for students, many of them among the generations that will feel some of the long term effects of climate change, to speak to the issues most important to them.

The book begins with a look at the environmental implications of climate change.

Boisclair and Jameus look at the economic value of wetlands and the link to climate damage mitigation and carbon sequestration. Panagiotis Tsigaris, writing later in the first part of the book, uses the same database to look at valuing nature-based solutions to climate change. The Tsigaris chapter was surprising to me, given the finding that grasslands and savannahs provide the most ecosystem value in the context of climate change, with values orders of magnitude higher per hectare than tropical forests.

Piggin looks at one of the most compelling positive feedback loops in climate change: wildfires. Last year, John Vaillant's wonderful book *Fire Weather* brought to the masses the link between warming temperatures and conditions which exacerbate wildfires. Piggin adds an interesting look at the emissions implications of wildfires, highlighting a short term positive feedback effect. Two other parts of the wildfire and climate feedback loop are explored in chapters by Escobedo and Gammie. Escobedo looks at forestry implications and positive feedback of pine beetle infestations and wildfires. And Gammie writes of a climate change impact that was news to me: blister rust on pine trees. The changing climate exposes vast white pine forests to this pest, much as was the case with pine beetles in years past.

In a similar vein, Keerat Sidhu takes us much further south, to the drought-riddled Amazon rainforest. Here, Sidhu looks at the challenge of deforestation through a climate change lens, documenting the impact of deforestation on Brazil's emissions mitigation trajectory, and tracking the implied social costs of carbon from the foregone sequestration. The shocking statistic that "the loss of forest in Brazil is equivalent to 26% of Canada's land and 33.5% of Canada's forests," caused me to gasp. The sheer scale of the destruction in one of our world's most important ecosystems is breathtaking. Troy Ssebanakitta writes about the challenge of preserving Ugandan forests under threat from climate change, and the knock-on threat to various endangered species that accompany the threat to the forests themselves.

Alexander Urquhart looks at the impact of the oil sands on future generations, a topic very near to my interests over the years. Urquhart canvasses the challenges facing the oil sands, including high emissions intensity and land use impacts, and highlights the important role of government financing and support in enabling the expansion of oil sands production over time. The figures raised in the comment regarding the looming reclamation costs should give us all pause as we contemplate a world moving (perhaps too slowly) away from oil consumption.

The second section of the book looks at options for adaptation and mitigation.

Allan and Sladden look at one of the most daunting challenges we face in Canada: the impact of climate change on Indigenous communities, in particular in the north and near-north. A complex array of climate impacts, from changes in fisheries and wildfire patterns, to alterations in sea ice cover and loss of permafrost impact Indigenous communities. Allan and Sladden also provide an important reminder of the impact of events like the Lytton wildfire on Indigenous-owned businesses and community administration and support structures.

Croteau and Guay look at one of the more interesting areas of climate impact in Canada: agriculture. They examine the potential for technology in the form of precision agriculture to enhance adaptation to climate impacts. While we generally see the emphasis on warmer temperatures, longer growing seasons, and perhaps more rain in some areas as positives of climate change for agriculture, farmers will also face more drought, large precipitation events, and heatwaves, and potentially even more cold snaps. Each of these raise important adaptation challenges in Canadian agriculture. In a later chapter, Alison Waterhouse examines the impact of climate on soils and, specifically, threat of soil erosion and potential retention techniques that become crucial in the context of climate change.

Adria Huser asks a pressing question of the global community: is it too late to limit warming to 2°C? The title masks a more nuanced question in the chapter itself, which is more focused on the adoption of renewable electricity generation than on global climate mitigation. We know that cleaning electricity generation is a key part of the global energy transition as it in turn enables even larger emissions reductions through the electrification of industrial and transportation activities. But, it’s also important to remember that a lot of emissions come from sources other than electricity generation and, in some ways, clean power has become one of the low-hanging fruit of climate change mitigation.

Lindsay and Chretien look at sea level rise and the consequences of this slow-moving but potentially devastating consequence of a warming world. The map they share in the chapter is one of the more compelling figures in the book, although it looks at a relatively extreme 6m sea level rise scenario. The map serves to highlight what will be true at the more moderate sea level rise expected this century: impacts will be felt almost everywhere. We can adapt to sea level rise, to some degree, but adaptation everywhere adds up to some very big bills to pay!

Dipika Popatlal looks at a more local, coastal issue in southern France and the terrifying caption on the map of the land to be under *annual* flood levels by the end of this century. When you look at the local impacts in Popatlal's chapter, and scale them up to the global level discussed by Lindsay and Chretien, the motivation for mitigation to reduce the impacts to which we will all need to adapt becomes clear.

And, in a related adaptation challenge, Kyra Williamson looks at the impact of wetlands on mitigation of climate impacts. Wetlands provide a very important buffer for the extreme rainfall and drought events that climate change will bring. Williamson rightly argues not only for wetland preservation, but for restoration which is a much larger challenge.

While it comes much later in the book, I found that a chapter from Olivia Davey on valuing marine ecosystems would have blended better with the questions in this section. Valuing our ecosystems and the services they provide is crucial to a coherent response to climate change. And, along the same line, Street and Magdolen highlight the importance of the fishery to global food security and in-turn the impact of climate change on fisheries. The chapter also highlights the differing impacts between the tropics where fisheries will face losses and the more temperate climates which may see positive impacts. As fish stocks move away from the regions that depend on them, the effects could be catastrophic.

The third section of the book looks at emissions reduction and alternative energy technology.

Brown and Floen look at the financial implications of electric vehicles for consumers. I was surprised at the degree to which their results supported hybrids rather than battery electric vehicles, but this is something I expect to change as both the cost of batteries drops and the ability to value-stack their storage and demand flexibility capabilities grows. Teryn Cameron looks at one of the challenges of electric vehicles in Canada: cold weather battery degradation. It would be interesting to see how much this weighs on Canadian consumers and how this has changed as overall ranges for electric vehicles have increased. Finally, Zachary Johnson looks at the potential for hydrogen fuel cell vehicles. I feel like this will be an interesting chapter to look back on in a few years, as it seems that infrastructure and technological progress are both working against hydrogen vehicles at this point and favouring electrics.

Kaboni and Viesner look at geoengineering – a means to rapidly mitigate the impacts of climate change. While I would not have classified carbon dioxide removal as a subset of geoengineering, I think the contrast between two technologies to reduce forcing directly is interesting. It follows a chapter by Patrick Izett that looks at how we can use satellite technology to identify methane leaks which, like geoengineering, can have more rapid impacts than the reduction of carbon dioxide. Methane abatement also extends beyond oil and gas, to agriculture and land use changes.

Finally, Molai and Thomson offer up a chapter on migration in the Sahel region in Africa, one of the regions most affected by climate change. Migration in general is one of the under-considered aspects of climate change and will place pressures on governments in and adjacent to severely affected regions. We are already seeing evidence of our incapacity to deal with this impacts without massive upheaval, and as climate change worsens, we are unlikely to improve in our capacity to welcome newcomers.

The final section of the book looks at national mitigation policies. First, Mutrie and Oleyakin look at the likelihood that Costa Rica will meet its targets, and speaks to the challenges of decarbonizing transportation. Conor Brown writes on Canada and finds that Canada is unlikely to meet its own targets and that Canada's targets are themselves likely to be seen as lax on the global stage.

As a whole, the book paints a picture of a cohort of students deeply concerned about the impacts of climate change and the capacity of our economic system to value the damages involved appropriately. I was surprised by the mix of pessimism and optimism with respect to energy and abatement technology options. And, while the final section can't be read as a representative sample of how the authors collectively feel with respect to Canada's efforts on climate change, the fact remains that Canada is not on track to meet its targets and that while I might personally disagree with this assessment, the international community sees Canada's efforts to mitigate climate change and its targets to lag where we should be.

Congratulations to all the authors and to their capable editor and mentor, Peter Tsigaris.

— Andrew Leach

Andrew Leach is a prominent Canadian environmental economist known for his expertise in energy and environmental policy, particularly related to climate change. He is a professor at the University of Alberta in the Faculty of Law and the Alberta School of Business, where he focuses on energy markets, environmental regulations, and the intersection of economics and law. With over 20 years of research experience, he also co-directs the Institute for Public Economics at the university. Previously, Leach served as a professor at the Alberta School of Business.

Leach earned his bachelor's degree in environmental science and master's degree in economics from the University of Guelph, followed by a Ph.D. in economics from Queen's University and a master's degree in constitutional law from the University of Alberta. Before his current roles, he was a teaching fellow in economics at Queen's University, an assistant professor at HEC Montréal, and a visiting scholar at Environment Canada's Strategic Policy Branch. Additionally, he directed the Centre for Applied Business Research in Energy and the Environment (CABREE) from 2014 to 2022.

Leach's interdisciplinary background in environmental science, constitutional law, and economics has positioned him as an advisor to governments on climate change and energy policy. He notably chaired Alberta's Climate Leadership Panel in 2015. As an expert, Leach has testified before several parliamentary committees and consulted for various governmental bodies, including Environment and Climate Change Canada and the National Roundtable on the Environment and the Economy (NRTEE). A prolific writer, he has authored over 200 articles for outlets such as CBC News, The Globe and Mail, and Maclean's.

Outside academia, Leach dedicates time as the board chair for REACH Edmonton Council for Safer Communities and is actively involved with the Edmonton Juventus Cycling Club, reflecting his passion for cycling. See: https://apps.ualberta.ca/directory/person/aleach

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Dedication

To all my students over the past 35 years,

This book is dedicated to each of you who have journeyed through the fascinating world of economics with me. Your curiosity, diligence, and enthusiasm have not only enriched our classroom but have also profoundly impacted my career and thinking. Thank you for being a part of my academic voyage, for sharing your insights, and for continuing to inspire the work that goes into these pages.

With gratitude and admiration,

Panagiotis (Peter) Tsigaris

Introduction to the Book

Introduction to the Book by Peter Tsigaris

This anthology book is a contribution from my students in an undergraduate course called the Economics of Climate Change. Students came from a variety of backgrounds and disciplines. Many were from the natural resource management degree, while others were from business, science, or arts. Initially, my students were exposed to the science of climate change during the first three weeks before getting into the economics of climate change. These first few weeks were necessary since economic analysis and policy cannot be done without a strong foundation of the science that informs us about emissions and climate change.

My students and I saw the climate change issue as one of the biggest market failures the world is facing. Anthropogenic-caused climate change is a negative externality, as it affects future unborn generations who are not participating today in the market. The atmosphere, oceans and land acting as carbon storage are common (collective) resources and can lead to the tragedy of the commons since there is no global governance institution. Furthermore, climate change mitigation is a global public good in that the benefits are non-rival, and no one can be excluded from enjoying the benefits of policies to reduce the damages. However, global public goods suffer from free riders if there is no global authority to punish free riders. Finally, climate change is seen by my students as a global, as opposed to local, problem, because:

- Its impact is long-term and persistent.
- It has both intra-regional and intergenerational equity inequities.
- Uncertainty and risk is pervasive.
- There are potentially significant and irreversible damages.

No wonder climate change is one of the biggest market failures the world is facing (Stern, 2008).

We explored the historical and future potential trends in GHG and fossil fuels under alternative scenarios. We framed the GHG emissions problem within the IPAT framework to assess the main drivers of CO_2 emissions. Namely, we looked at population, affluence and technology's roles in driving or reducing emissions. We examined climate change within the framework of Malthusian and Post-Malthusian societies, emphasizing environmental constraints (Tsigaris & Wood, 2024). We discussed the impact of climate change on growth and economic development. We analyzed and debated the stabilization of GHGs to net zero and the cost of achieving such ambitious targets. Various mitigation policies, with their benefits and costs, were brought forward for analysis, such as carbon taxes, permit markets, and incentives for green technologies. We assessed adaptation measures. The international collective action and its challenges were illustrated by conducting a mock United Nations Framework Convention on Climate Change conference, whereby students in groups were representing the US, China, India, Europe, and other developed and developing nations and making pledges to keep temperature anomaly below 2°C relative to pre-industrial levels. The course ended with students engaging in experiential learning, whereby they figured out a cause-and-effect pattern of human activity and its implications using cards from Climate Fresk.

Students selected their commentary after a month into the course, which I reviewed and gave them the green light to proceed. The commentary had some requirements, such as keeping it around 600 words, including at least one table or figure, and using a few citations from academic research published in peer-reviewed journals. Meanwhile, I completed my commentary early in the semester so my students had an idea of what I expected from them. My commentary attempted to provide a perspective on the value of global climate regulation services of the world's biomes using the Ecosystem Services Valuation Database (ESVD) developed by Brander et al. (2023), which I plan to publish with my colleague Dr. Lauchlan Fraser, a professor in the natural resource department who studies reclamation and is an expert in ecology and community. Students submitted two drafts of their commentary during the semester, and I provided constructive feedback. They used this feedback to revise their work until they submitted a final version at the end of the semester, which is now available in this book. Allowing students to revise their work is a method I have been using for the last few years, and the result is significantly better quality of work from students (Tsigaris, 2021). I am very proud of my students' work. I read commentaries from their research that were an eye-opener for me. I am confident that you will find this work of significant value, and I am looking forward to your thoughtful and insightful feedback.

Sincerely yours,

Panagiotis (Peter) Tsigaris

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INTRODUCTION

Introduction

Climate change represents one of the most significant challenges facing our global community today, with far-reaching implications for both natural environments and human societies. N*avigating Climate Economics: Perspectives for a Sustainable Future* brings together a diverse array of perspectives and in-depth analyses exploring the complex intersections of climate change with natural and socioeconomic systems. This anthology, composed of contributions from my undergraduate students and myself, provides commentaries for protecting nature, potential pathways, and policy measures necessary to steer our planet toward a more sustainable future.

The compilation of perspectives is structured into several thematic sections, each exploring different aspects of climate science and economics. Through these sections, the book examines the practical and theoretical frameworks that can be employed to understand and address the economic impacts of climate change. Contributors provide insights into climate change and environmental impact, adaptation and mitigation strategies, economic assessment of technologies, and feasibility of targets.

The book includes the following perspectives, commentaries and opinions:

Climate Change & Environmental Impacts

The global economic value of the climate regulation of inland wetland ecosystems.

Clara Boisclair and **Brook Jameus** provide a commentary on the economic value of climate regulation, which is essential in mitigating floods and supporting biodiversity.

Climate change in British Columbia's forest sector.

Natasha Escobedo explores the impact of climate change on forestry and its economic consequences.

The science & economics of blister rust on pine in North America due to climate change.

Chantal Gammie assesses the economics and science behind North American pine degradation influenced by climate change.

British Columbia wildfires: A problem caused by & contributing to climate change.

Stephanie Piggin explores the dual role of how the increasing frequency of BC wildfires contributes to and is exacerbated by climate change.

Climate change & Brazil's Amazon rainforest.

Keerat Sidhu's commentary discusses the effects of climate change on Amazon, the deforestation impacts, and ecological and atmospheric changes.

The economics of the conservation of Mabira forest under climate change.

Troy Ssebanakitta explores the economic analysis of preserving Uganda's forest under changing climatic conditions.

The value of global climate regulation services of the world's biomes.

Peter Tsigaris assesses the economic value of climate regulation by biomes essential for ecosystem stability and human survival.

How will the Alberta oil sands affect future generations?

Alex Urquhart provides perspectives on the reclamation costs of the oil sands and the impact on future generations.

Climate Change Adaptation & Mitigation Strategies

Climate change, inequality, & Indigenous communities in Canada.

Meghan Allan and **Molly Sladden** explore the disproportionate impacts on Canadian Indigenous communities, socioeconomic inequalities, and adaptation needs.

Precision agriculture: Navigating climate change challenges for sustainable & profitable farming.

Alexandre Croteau and **Alicia Guay's** commentary explores adaptation measures in farming, including technology-driven, sustainable, and economically viable practices, to navigate climate challenges.

Is there enough time to limit warming to 2°C? The cost & speed of a renewable energy transition.

Adria Huser analyzes the costs and speed of transitioning to renewable energy to meet climate goals.

The economic implications of sea-level rise for coastal cities & adaptation strategies.

Ella Lindsay and **Emma Chretien** explore the implications for coastal cities and the economic assessment of adaptation strategies to rising seas.

Coastal adaptation measures in the Aquitaine region of southern France.

Dipika Popatlal comments on measures needed to combat rising sea levels and erosion in Southern France.

Navigating the waves: Analyzing climate change impacts on global fisheries & socioeconomic resilience.

Andres Street and **Lubo Magdolen** comment on the economic and social impacts of the migration of fisheries due to climate-induced changes.

Soil degradation & mitigation techniques: A means to economic success.

Ali Waterhouse provides information on techniques and their economic benefits essential for sustainable agriculture and environmental health.

Can we mitigate the costs of flood damage through wetlands?

Kyra Williamson's perspective argues that wetlands are environmental sponges and prevent flooding. Restoring degraded wetlands pays off.

Technological & Economic Assessments

Combustion engine vs. electric vehicle: An economic assessment.

Trayton Brown and **Alec Floen** provide perspectives comparing the total economic cost of traditional and electric vehicles.

Cold climate conditions & electric vehicle battery degradation.

Teryn Cameron tackles the effects of cold climates on electric vehicle batteries.

Economics in a changing climate: Investigating the economic consequences of climate change on marine ecosystems.

Olivia Davey assesses the economic consequences and adjustments needed due to climate change in marine sectors.

Satellite technology, methane, & climate change economics.

Patrick Izett explores the role of monitoring climate change and the economic implications of satellite data for climate strategies.

The potential of hydrogen fuel cell vehicles.

Zachary Johnson discusses the potential of hydrogen as a clean alternative to fossil fuels in transportation.

The economic feasibility of geoengineering solutions.

Clinton Kaboni and **Lauren Viesner** conduct an economic analysis of large-scale interventions to artificially modify

Earth's climate.

Unravelling threads of change: Economic & climate change-induced migration in the Sahel.

Ashley Thomson and **Naledi Molai** assess the economic and climate factors driving migration and impacts in the Sahel region.

Specific National/Regional Policy Assessments

Will Canada hit net zero emissions by 2050?

Conor Brown argues that Canada never hit its targets in the past, and there is no strong evidence that it will hit its ambitious targets for 2030 and 2050.

How feasible are the 2050 targets for Costa Rica?

Ainsley Mutrie and **Moses Oyelakin** discuss the feasibility of meeting their targets by 2050 by reducing transportation emissions.

CLIMATE CHANGE & ENVIRONMENTAL IMPACTS

British Columbia Wildfires: A Problem Caused by & Contributing to Climate Change

STEPHANIE PIGGIN

Introduction

Wildfires are a naturally occurring phenomenon that can be caused by many natural occurrences but also human activities. The cause and effect are increasingly intertwined with climate change dynamics, necessitating a comprehensive understanding (Higuera, 2015). One crucial aspect to consider is the social cost of carbon (SCC), which measures the external cost of burning carbon and plays a significant role in quantifying the economic impact of wildfires exacerbated by climate change.

B.C. Wildfires & Carbon Emissions

Figure 1: *Ashcroft Reserve wildfire by Look Lake, BC (Shawn Cahill/ Wikimedia Commons).* CC BY-SA 4.0

During a wildfire, a lot of particles and gases go into the atmosphere. Wildfires occur in different types of forests, which contain different varieties of trees, foliage, grasses, soils, and other factors that impact what particles and gases are emitted into the atmosphere (Prichard et al., 2020). Carbon dioxide is the most abundant greenhouse gas emitted during a wildfire.

Wildfires are increasing in number, as well as hectares burned. In British Columbia (B.C.), "forest wildfires in recent years have emitted more CO_2 than all fossil fuel burned by the population and industry in the province" (International Association of Fire and Rescue Services, 2023). For example, in 2017, "about 150 million tons of CO_2" went into the atmosphere due to B.C. wildfires that year. In contrast, in 2017, greenhouse gas emissions from fossil fuel emissions were approximately 64 Mt CO_2e. The CO_2 emissions from forest fires are about 2.3 times more than those of transportation, industry and built environment.

SCC of the Wildfires

With such increases in wildfire volumes, we must consider the social cost of carbon being emitted. “The SCC measures the external cost of burning carbon, so pricing carbon at its full social cost (e.g., by imposing a carbon tax) requires an estimate of the SCC” (Pindyck, 2019). According to Pindyck (2019), “on average, the beliefs of climate scientists imply a much higher SCC (around $300 or more) than do the beliefs of economists (which imply a SCC of around $170).” According to climate scientists, the SCC of B.C. wildfires since 2017 has been USD 267 billion, with 2023 at USD 118 billion. In comparison, the Gross Domestic Product for B.C. in 2023 is estimated at CAD 300 billion. In the last seven years, the over 6 million hectares burned across the province have led to 849 megatons of CO_2 emissions, almost double the emissions coming from economic activity. The economic impact of these wildfires is also vast. In B.C., CAD 115.4 million worth of property losses followed the forest fires of 2023 (Salas, 2023a). **Table 1** summarises the economic impact of B.C. wildfires from 2017 to 2023.

Table 1: Wildfires in British Columbia, 2017–2023

Period	**Number of Wildfires**	**Hectares Burned**	**CO_2 Emitted From Wildfires (megatons)**	**Cost Economists (millions of USD)**	**Cost Climate Scientists (millions of USD)**	**Cost Conservative Estimation (millions of USD)**	**GHGs From Economic Activity (megatons)**

2017	1,332	1,215,685	160	27,803	50,628	16,006	64
2018	2,080	1,355,271	178	30,995	56,441	17,844	66
2019	825	21,138	3	483	880	278	65
2020	649	15,000	2	343	625	197	61
2021	1,625	869,270	114	19,880	36,201	11,445	62
2022	N/A	134,900	18	3,085	5,618	1,776	63
2023	2,245	2,840,545	374	64,964	118,296	37,400	62
Total	8,107	6,451,809	849	147,554	268,689	84,948	444

Note. The 2023 CO_2 emissions relative to hectares burned are assumed to be the same for all other years. The 2023 emissions data were obtained from Depner (2024). Pindyck (2019), by conducting a survey, found that the social cost of carbon for economists to be $173.7 a ton, and climate scientists are at 316.3. When the author removes the outliers, it comes to $100 a tonne. GHGs from economic activity for 2022 and 2023 are estimations from Government of British Columbia (2023).

Conclusion

In summary, wildfires are a product of natural phenomena and human activities exacerbated by climate change. These fires' escalating frequency and intensity have profound economic implications, as evidenced by the substantial SCC associated with their emissions. Addressing these challenges requires a multifaceted approach that includes mitigation strategies, carbon pricing mechanisms, and proactive measures to minimize environmental and economic impacts. With a deeper understanding and implementation of sustainable solutions, we can build resilience and mitigate the adverse effects of wildfires for future generations.

Media Attribution

Figure 1: "Ashcroft Reserve wildfire – Look Lake, BC" by Shawn Cahill (2017), via Wikimedia Commons, is used under a CC BY-SA 4.0 license.

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The Global Economic Value of the Climate Regulation of Inland Wetland Ecosystems

CLARA BOISCLAIR AND BROOK JAMEUS

Introduction

Wetland ecosystems play a crucial role in sustaining both the environment and economies worldwide, providing a myriad of economic benefits. These ecosystems contribute significantly to global economic well-being through a wide range of ecological services. The economic value of wetland ecosystem services per hectare has been ranked first among all kinds of natural ecosystems (Dang et al., 2022). Yet the area of global wetlands reduced by about 35% between 1970 and 2015, indicating a need for increased conservation of these ecosystems. The economic value of wetland ecosystems lies in their capacity for water regulation and supply, waste management, food supply, biodiversity, fisheries, tourism, and most important to this short commentary, climate regulation (Dang et al., 2022; Sheergojri et al., 2023).

Economic Value of Wetlands

Wetlands act as natural buffers against floods and storms, protecting nearby communities and infrastructure (Dang et al., 2022; Sheergojri et al., 2023). This buffer reduces the need for disaster management, a known economic burden continuously growing as the impacts of climate change increase. Additionally, wetlands serve as effective water purifiers, increasing water quality by filtering out pollutants and excess nutrients (Mahlatini et al., 2020). This attribute reduces the expenses related to water treatment processes for municipalities and industries. Wetlands also play a vital role in supporting biodiversity, providing nurseries and habitats for various species (Mahlatini et al., 2020). This unique flora and fauna attract ecotourists such as bird watchers and reptile enthusiasts. These visitors generate substantial revenue for local economies through accommodations, recreation, and guided tours. Agriculture and fisheries (commercial and recreational) are some additional beneficiaries of wetland ecosystems and depend on the productivity of wetland ecosystems to function (Sheergojri et al., 2023). The cultivation of these lands contributes to global food security and provides livelihoods for millions (Mahlatini et al., 2020).

***Figure 1**: Lac Paradis (Cptcv/ Wikimedia Commons).* CC BY-SA 2.5

Calculating Economic Value

To evaluate the economic value of the climate regulation services provided by inland wetlands globally, we accessed the data within the Ecosystem Services Valuation Database (ESVD) (Brander et al., 2023). The ESVD provides monetary value for the global climate regulation services of the different earth's biomes per hectare and per year. Filtering the data to solely retain the inland wetland biome resulted in 863 observations. With this filter, inland wetlands include peatlands, marshes, swamps, seasonal floodplain marshes, episodic arid floodplains, and groundwater-dependent wetlands (Brander et al., 2023). From these wetland observations, 16 valuations fell under the ecosystem service of "climate regulation" in the Economics of Ecosystem and Biodiversity (TEEB) classification. The average global climate regulation services value of wetlands is evaluated at 1,029 Int.$/hectare/year based on 2020 prices (Brander et al., 2023). Recent studies suggest that the global area of wetlands ranges from 1.2 to 1.6 e9 hectares, and the greatest global wetland area is inland natural wetlands, sitting around 1.29 e9 hectares. (Davidson et al., 2023). As stated above, Dang et al. (2022) state a loss of roughly 35% of global wetland areas since 1970. **Table 1** provides the summary statistics based on the 16 wetland valuations from ESVD and the wetland loss.

Table 1: Global Climate Regulation Services Value of Wetlands

Wetlands Category	**Global Area (e9 ha)**	**# of Valuations**	**Average Int$/ha/year**	**Median Int$/ha/year**	**Standard Deviation**	**Min. Value**	**Max Value**	**Average value/year (e12 in Int$)**
Inland Wetlands	1.29	16	1,029	152	6,079	4.97	13,874	1.32
Loss Since 1970	0.69	–	1,029	–	–	–	–	0.71

Note. Based on data from: 2020 price levels (Brander et al. 2023); Surface area of inland wetlands (Davidson et al. 2023); and Wetland loss since 1970 (Dang et al, 2022).

Wetlands as Carbon Storage & Sequestration

One of the global climate regulation services wetlands provide is the storage and sequestration of carbon. Wetlands are estimated to store 35% of global terrestrial carbon despite only covering ~6%–9% of the planet's land surface, making healthy wetlands a positive externality on a global scale (Deng et al. 2022). Since the global soil carbon stands around 1,500 petagrams (Pg C, 1015 g, 1 billion tons or 1 Gt), 35% represents 525 gigatons (Gt) of carbon, which is 1,926.8 Gt of carbon dioxide (CO_2) or 1.93 trillion tons (525 Gt C x 3.67 = 1,926.8 Gt CO_2, divided by 1,000 to get trillion tons) (Nahlik & Fennessy, 2016). The social cost of a ton of CO_2 varies, but a recent study estimates it at $100 a ton conservatively (Pindyck, 2019). Economists value CO_2 at $173.7 a ton, while climate scientists value it at $316.3 a ton (Pindyck, 2019). According to the conservative estimate, the value of storing carbon would sit at ~ $193 trillion while, according to climate scientists, the value would stand at ~$610 trillion, and adds Int$1.32 trillion a year to this valuation in terms of sequestration (see **Table 1**).

Conclusion

Wetlands, like many other ecosystems around the globe, are no strangers to threats such as habitat loss, pollution, and climate change despite their vast economic importance (Dang et al., 2022; Sheergojri et al., 2023). Recognizing the economic value of wetland ecosystems is crucial for implementing effective conservation measures that balance preservation with sustainable economic development. Preserving and restoring wetlands is a necessary investment in the long-term health of both ecosystems and economies worldwide.

Media Attribution

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Climate Change in British Columbia's Forest Sector

NATASHA ESCOBEDO

Introduction

In this short commentary, we will explore the consequences climate change has posed on the forested ecosystems and how that impacts the forest sector of British Columbia. The assessment serves to aid in determining the best solution to the climate change crisis.

British Columbia's Forest Sector

In terms of global climate change mitigation, forests contribute largely to carbon sequestration in the form of carbon sinks (Xu et al., 2018), aiding in the reduction of greenhouse gas (GHG) emissions (Lemprière et al., 2017). Forested areas across the globe that are not affected by land use change can remove up to 8.8 GtC02/year (Xu et al., 2018) from the atmosphere, while it is predicted that the British Columbian forest sector has the potential to remove between 0.2-13.8 GtC02/year by 2030 (Xu et al., 2018). British

Columbia's forests account for 55 million hectares, where 95% are provincially owned (Xu et al., 2018).

Mountain Pine Beetle & Wildfires

Figure 1: *Kennedy Siding – Attacked Canopy in 2007 (Matthew Brown/ UBC Micrometeorology/Flickr).* CC BY 2.0

Since the early 2000s, British Columbia's forest sector has seen some devastating events that impacted the production and harvesting of timber (Corbett et al., 2015). Climate change has triggered, through cause and effect, irreversible damage to the forest sector through events such as the Mountain Pine beetle (MPB) epidemic, which devastated approximately 18.3 million hectares of forested ecosystems, causing a $57 billion cumulative loss in GDP in B.C. (Corbett et al., 2015).

Wildfires in recent years have been extremely devastating in terms of forested ecosystem damage, where the damages each year seem to be greater than the last and are predicted to increase in future years. With this, cumulatively, wildfire has devastated 7.7 million hectares of forested and residential land in B.C. since 2008 (BC Wildfire Service, 2024). Due to the insurmountable damage caused, the economic impact is approximately $17 billion cumulative loss in GDP; however, this is an approximation as limited data is available (see **Table 1**) (BC Wildfire Service, 2024).

Globally, forests are extremely important to the carbon cycle as long-term storage and the largest terrestrial sinks for CO_2 (North & Hurteau, 2011). Climate change has altered the frequency and severity of natural disturbances, resulting in increased release of stored carbon within the B.C. forest sector. This increased release of CO_2 has been recorded through the MPB epidemic, which is responsible for 270 megatons of stored CO_2 released, and through the wildfire seasons, which released approximately 46 megatons of stored carbon within the past 20 years alone (see **Table 1**).

Table 1: Economic Impacts of Climate Change on B.C. Forest Sector

Climate Change Damaging Agent	**Damage (ha)**	**Average C Released (20-year period)**	**Cumulative Economic Impact ($ loss 2000–2023)**
Pine Beetle Epidemic	18,300,000	270 Mt	$57.37 billion GDP $90 billion welfare
Wildfire	7,761,742	46 Mt	$17.1 (approx.) billion GDP

Note. Data from Corbett et al., (2015) and BC Wildfire Service (2024)

SSC of Damages

Carbon sequestration from the atmosphere is an important part of reaching carbon targets (Smyth et al., 2020); however, climate change is making these goals harder to reach due to the ongoing impacts of climate change, causing these mass devastating events that release insurmountable amounts of carbon into the atmosphere and damaging these carbon sinks (Kirilenko & Sedijo, 2007). Estimations of the social costs of carbon (SCC) are crucial for developing climate policies (Pindyck, 2019). With the insurmountable damage seen in B.C.'s Forest sector by the mountain pine beetle epidemic and the wildfire activity, the estimated SCC can be used to help determine the right policies to implement.

Table 2 shows the SCC for the cumulative impacts of wildfires and the MPB epidemic.

Table 2: Climate Change Damages Using Social Costs of Carbon (SCC)

Social Cost of Carbon ($/Mt)	**SCC per ton**	**Total SCC of Wildfires**	**Total SSC of Pine Beetle Epidemic**
Economics	173.7	$8 billion	$46.9 billion
Climate Change	316.3	$14.6 billion	$85.4 billion
Conservative	100.0	$2.7 billion	$27.0 billion

Note. Data from Pindyck (2019), Corbett at al. (2015), and BC Wildfire Service (2024)

Media Attribution

Figure 1: “Kennedy Siding – Attacked Canopy in 2007” by Matthew Brown and UBC Micrometeorology (2007), via Flickr, is used under a CC BY 2.0 license.

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The Science & Economics of Blister Rust on Pine in North America Due to Climate Change

CHANTAL GAMMIE

Introduction

Climate change is warming the Earth, causing changes in the landscape and creating conditions optimal for diseases to thrive. The disease triangle shows that three elements are needed for a disease to grow and establish itself successfully (Sturrock et al., 2011). They are a susceptible host, a virulent pathogen, and a favourable climate. The changing climate can increase the prevalence of a favourable environment, creating an optimal environment for a pathogen to attack a host (Dudney et al., 2021). A particularly problematic disease is blister rust in pine stands in British Columbia.

Blister Rust & Climate Change

Figure 1: *White pine blister rust (André Carpentier et al. / Government of Canada) Government of Canada Terms and Conditions*

Blister rust affects hard pines, creating a fungus on the tree's inner bark. It causes deformity, growth reductions, mortality, and decreased seed production (Johnson, 1986). The pine tree acts as the host in the disease triangle for the fungus to grow during favourable conditions. Blister rust is causing major mortality and health issues in pine, creating concerns for the future use of pine for lumber.

Climate change is causing an environment that enables this disease to thrive in North America. Blister rust needs a cool environment with sufficient moisture to thrive (Dudney et al., 2021). Climate change is shifting species abundance from more arid regions to colder regions in the north that were previously considered inhospitable. Aridity plays a critical role in changing host-pathogen interactions, and the increasing drought in arid environments may reduce infection rates by inducing stomata closure and making it more difficult for pathogens to access the host. Whereas cooler, more northern areas provide the moisture needed for pathogen reproduction (Dudney et al., 2021).

Blister rust ranks as one of the worst tree pandemics in history. The impact it has had in recent years, and is continuing to have, on pine stands has the potential to cause major damage to the timber industry. White pine blister rust has been particularly problematic in Canada, and **Figure 2** shows the growing distribution of infection across the country. The economic setbacks can be devastating if the disease spreads to areas not used to fighting this disease, which are more susceptible to damage, with no alternate species planted.

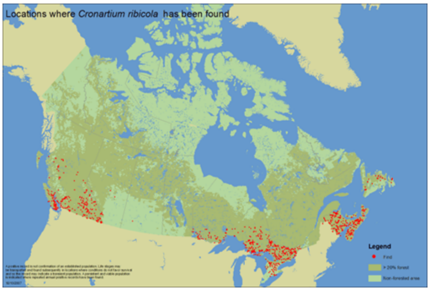

***Figure 2**: Locations where Cronartium ribicola has been found (Natural Resources Canada/ Government of Canada). Government of Canada Terms and Conditions*

Economic Loss

A similar problem arose with the mountain pine beetle outbreak. More than 53% of merchantable pine had been attacked, and Corbett et al. (2015) estimated a cumulative present value loss of $57.37 billion in GDP and a $90 billion decline from 2009 to 2050. The pine beetle outbreak showed that economic loss from such an outbreak can be large, so it would be in our best interests to prevent a similar outbreak from happening again. The loss of profitable lumber from blister rust may be substantial, and the cost of applying control measures to these stands may be as well.

Control Measures

A control measure may be alternate host species removal, as each tree requires an alternate host plant to be infected first before it transfers to the tree. The cost of alternate species removal, or the thinning of infected trees, would be high in cost. As of now, the question is whether to invest in control measures to limit the number of pine trees infected or plant alternate conifer species that do not get infected by blister rust, although it may not be as desirable in the lumber industry.

Deployment of pines from the south into other areas has shown to be successful in combating fusiform rust. Seedlings with a resistant gene from control mating have been deployed over forest plantations struggling with rust issues. Sneizko et al. (2021) state the estimated return investment for every dollar spent on fusiform rust resistance is $5–20. If the same can be done to other strains of rust with similar economic gain, there is a good incentive to put in the time and initial investment into more genetic research and experimentation. Hagle and Grasham (1988) performed an experiment to determine the net value of stands with either no treatment, pruning, or pruning with excising. Their study shows the greatest net value was with the treatment of both pruning and excising, while the least net value resulted from the no-treatment control.

The results of these two studies show that there may be the most economic benefit from exerting control measures on infected stands to decrease the negative effects the disease has on the trees and hope that the trees can still grow to be good lumber that can be economically benefited from.

Media Attributions

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Figure 2: “Locations where Cronartium ribicola has been found” by Natural Resources Canada (2007), via Government of Canada, is used under the Government of Canada Terms and Conditions.

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Climate Change & Brazil's Amazon Rainforest

KEERAT SIDHU

Introduction

Rich in biodiversity, the Amazon rainforest is crucial in controlling the global carbon budget and dictating the course of the climate. Nonetheless, there are signs that the effects of climate change could be particularly detrimental to the Amazon rainforest. One of the world's largest carbon sinks, the Amazon rainforest contains between 150 and 200 Pg C in its soils and live biomass (Feitosa et al., 2023). The Amazon efficiently collects CO_2 through photosynthesis, contributing around 10% of the world's net primary productivity and carbon stocks in terrestrial ecosystems. Nevertheless, continuous deforestation in the Amazon region has increased greenhouse gas emissions and interfered with carbon storage capacity to efficiently sequester carbon.

Deforestation in the Amazon Rainforest

Figure 1: *Juma River in Amazonas, Brazil (Dr. Alexey Yakovlev/Flickr).* CC BY-SA 2.0

Alarming levels of fragmentation and significant changes in carbon stocks have resulted from surging deforestation rates (Silva et al., 2021). Approximately 52% of Brazil's emissions (e.g., 1.1 billion out of 2.2 billion of CO_2e in 2020) are caused by fires and the conversion of forests and natural pastures (de Vasconcelos et al., 2013). Additionally, the conversion of forests and natural pastures amounts to 35% of the country's total carbon storage in tropical forests (Barros & Fearnside, 2016). According to estimations, deforestation accounts for over 47% of the total emissions accumulated since the 18th century, making it a significant contributor to greenhouse gas emissions even today (Lapola et al., 2023). Deforestation rates in the Brazilian Amazon exceeded 20,000 km^2 in 2004, despite the Amazon rainforest's critical role in delivering a variety of ecosystem services (Urzedo et al., 2020). As global fossil-fuel burning has risen, the Amazon has absorbed CO_2 from the atmosphere, helping to moderate the global climate.

Contributors to Deforestation

Unauthorized entry into protected territory has been made easier by ineffective law enforcement and unlawful activity, which is mainly driven by the growth of cattle ranching and illegal mining (Van Solinge, 2020). Deforestation rates have increased because of this (Climate Action Tracker, 2023). Emissions are predicted to increase steadily in the absence of policy changes, severely impeding Brazil's progress toward its climate targets. Early research points to previously unheard-of levels of deforestation in the Amazon region by the middle of 2022 (Climate Action Tracker, 2023). **Table 1** summarises the valuation of loss from forest area decline due to deforestation from 1990 to 2020.

With its present policy, Brazil's emissions, excluding those from its land sector, have largely plateaued, and no rise is anticipated for the balance of the decade. However, to meet its 2030 targets and adhere to the 1.5°C warming goal, Brazil will need to significantly reduce its emissions within this decade (Climate Action Tracker, 2023). The present course of Brazil's policy emissions is not meeting the 1.5°C target, which might result in a 3°C to 4°C increase in world temperature if other countries were to follow suit. According to what it said in its 2023 Nationally Determined Contributions (NDC) proposal, Brazil hopes to achieve "climate neutrality" by 2050. However, Brazil has not yet provided the United Nations Framework Convention on Climate Change (UNFCCC) with a long-term plan (Climate Action Tracker, 2023).

Table 1: Valuation of Loss From Forest Area Decline Due to Deforestation, 1990–2020

Period	**Forest Area (% decline in km^2)**	**Deforestation (in millions of ha)**	**Valuation of Loss (in millions of ha)**
1990–2000	– 6.4%	37.8	7,673
2000–2010	-7.2%	39.5	8,019
2010–2020	-2.9%	15.0	3,045
1990–2020	-16.5%	92.3	18,737

Note. Annual growth rates of forest area were computed from World Bank (n.d.)

SCC of Deforestation

The social cost of carbon (SCC) can be used to assess 150 to 200 billion of carbon. The SCC is calculated with a discount rate as the present value of the future consumption reductions brought about by the extra ton of emissions (Pindyck, 2019). This calculation is in line with the basic idea of an SCC, which is the economic harm resulting from each additional ton of CO_2 released, independent of the economic and climatic factors that create the harm. Economists price carbon at USD 173.7 and climate scientists at 316.3 per ton of CO_2. Hence, let the carbon stored be 175 billion tonnes of carbon or 642 CO_2 (175*3.67). Then, according to climate scientists, the value of stored carbon is USD 203 trillion (Pindyck, 2019).

Canada's forest area is approximately 362 million ha, whereas the total land area is 998.5 million ha (Natural Resources Canada, 2024). Canada's deforestation rates are stable, with less than half of 1% deforested since 1990. In comparison to the size of Canada, the loss of forest in Brazil is equivalent to 26% of Canada's land and 33.5% of Canada's forests.

Conclusion

The Amazon rainforest is vulnerable to the damage caused by deforestation. With Brazil's lack of a current long-term plan to mitigate the amounts of deforestation, the increasing greenhouse gas emissions negatively affect carbon storage capacity (Feitosa et al., 2023). Ultimately, it will increase the amount of forest loss in Brazil.

Media Attribution

Figure 1: "Juma River Igapó" by Dr. Alexey Yakovlev (2010), via Flickr, is used under a CC BY-SA 2.0 license.

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The Economics of the Conservation of Mabira Forest Under Climate Change

TROY SSEBANAKITTA

Introduction

In this short commentary, we explore the economics of conserving the Mabira Forest in Central Uganda under climate change. The goal is to show that the benefits of conserving the forest outweigh whatever benefits come from cutting it down. This assessment can aid in determining the best land use solution in line with mitigating the climate change crisis.

The Mabira Forest

Value

Figure 1: *Mabira has natural habitat of 312 species of trees (National Forestry Authority/ NFA). Used with permission.*

The Mabira Forest is a rainforest covering about 300 square kilometres (30,000 hectares), some of which could be sold to a more polluting country for a given number of years as carbon credits (Bonnerot, 2023). The money generated from selling the credits could go to the development of Ugandan infrastructure, such as roads and hospitals or used to pay debts to countries like China.

The Mabira Forest is home to endangered animal species such as the Lophocebus ugandae (Grey-cheeked mangabey). It is also home to 200 plant species that are used for medicinal purposes. Medicinal plants form an integral part of many healthcare systems in Uganda. In a study by Asiimwe et al. (2021), of the 136 medicinal plants recorded, 44% were used for digestive disorders, 38% for respiratory and 36% for dermatological disorders. Hoslundia opposita Vahl (bird gooseberry) was mentioned by 71% of the study respondents for treating 22 disease conditions, and about 61% of the plants were harvested from wild habitats. As of 2019, the annual forest recreational value was 2.1 billion UGX (577,446 USD) (Tugume et al., 2022).

Being one of the most extensive forests in East Africa, it absorbs large amounts of carbon dioxide and heat. It is also a rain catchment for areas supplying the Ssezibwa and Nile Rivers through convectional rainfall. Central Uganda, where the forest is located, is at a low risk of wildfires, making it ideal to be used for carbon offset projects due to its persistence and longevity.

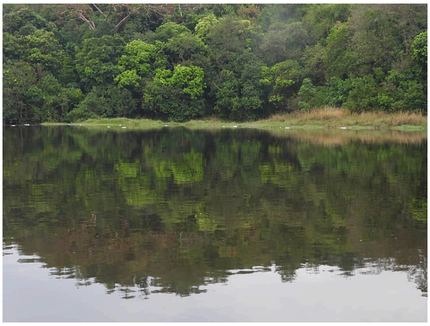

Figure 2: *Mabira Forest in Uganda (Ndahiro derrick / Wikimedia Commons)* CC BY-SA 4.0

Problems

The Mabira Forest still faces the problem of malicious fires set by hostile communities in retaliation for a refusal to allow them access rights and land conflicts between communities and agro-commodity companies (Opige et al., 2023). There is also the issue of the government giving away large portions of the forest for planting sugarcane fields (East African Jungle Safaris, n.d.). The problem of irreversibility, as it is difficult to plant trees in areas they have never been before, is the process known as afforestation (Piazza & Roy, 2019). Favourable areas for afforestation are often found amidst dense population centres. At the same time, the remaining land typically consists of barren expanses or regions at heightened risk of wildfires, landslides, and other natural disasters.

Conclusion

In conclusion, safeguarding the Mabira Forest remains paramount for the Ugandan government due to its multifaceted significance to the nation and the global community.

Media Attributions

Figure 1: "Mabira has natural habitat of 312 species of trees" by National Forestry Authority (n.d.) (Uganda) [website] is used with permission.

Figure 2: "Mabira forest in Ugandaa" by Ndahiro derrick (2020), via Wikimedia Commons, is used under a CC BY-SA 4.0 license.

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The Value of Global Climate Regulation Services of the World's Biomes

PANAGIOTIS TSIGARIS

Introduction

In this short commentary, we explore the value of the global climate regulation services within the Ecosystem Services Valuation Database (ESVD) across marine and terrestrial biomes (Brander et al., 2023). The aim is to place a value on the biomes service of global climate regulation. The assessment can aid in determining the best nature-based solution to the climate change crises (Griscom et al., 2017). Biomes contribute to stabilizing and regulating Earth's climate, including the sequestration and storage of greenhouse gases by forests, wetlands, grasslands, and oceans. The latter role is absorbing CO_2 and heat, although it results in acidification, destroying marine life. Ice sheets and polar alpine biomes also play a significant role by reflecting sunlight and keeping the Earth's temperature cooler than it would be without these biomes.

Valuation of Global Climate Regulation Services

Figure 1*: Lac du Bois Grasslands Protected Area north of Kamloops, B.C. (Straitgate/Wikimedia Commons)* CC BY-SA 3.0

The surface area of the biomes was measured using data from published research to place a monetary value on global climate regulation. The ESVD provides data on the value of global climate regulation services per hectare (ha) per year of the biomes (Brander et al., 2023). Initially, all 9,500 observations were extracted, 546 of which had "climate regulation" as ecosystem services 1 (ES_1) from the Economics of Ecosystems and Biodiversity (TEEB) and the "global climate regulation services" from the Ecosystem Accounting (SEEA). Of the 546 observations, 350 had only one primary ESVD2.0 biome, and the other biomes were removed due to their joint contribution. **Table 1** provides summary statistics after sorting the 350 observations according to ES_1.

The open sea is the largest biome, estimated at 33.07 billion ha, followed by rangelands, natural grasslands, and savannas, representing 3.50 billion ha. Forests have a surface area of 4.2 billion ha but are divided into two forest biomes. Although urban and industrial areas occupy the most minor surface on Earth, they release the most GHG emissions.

Biome Values

The highest global climate regulation services valuation arises from the rangelands, natural grasslands, and savannas (RGS), with an average price/ha/year at Int$24,613. The second valued biome for climate regulation is coastal systems at Int$15,982/ha/year. The median values are lower, showing the influence of high valuations pulling the average much higher. The highest valuation with a median is the urban and industrial areas, followed by the polar alpine and RGS biomes. The degradation of the alpine biome impacts the Earth's albedo, or its capacity to reflect the Sun's rays, which in turn increases global temperatures, exaggerating climate change. Most likely, valuation increases over time due to a reduced supply of services arising from the degradation of the biomes. Furthermore, demand for such services may have increased over time due to increased living standards. Hence, people value ecosystem services more as they degrade.

Figure 2: *Grasslands around Kamloops (Mara trail), British Colombia, Canada (Ghune/ Wikimedia Commons). CC0 1.0 Universal*

Rangelands, Natural Grasslands, & Savannas

RGS is crucial for carbon sequestration and the global carbon cycle (Conant, 2012; Lorenz & Lal, 2018; Bai &

Cotrufo, 2022). About a third of terrestrial carbon is stored in grasslands (Bai & Cotrufo, 2022). This study indicates a high valuation of RGS ecosystem services for global climate regulation relative to the other biomes. Grasslands store 343 Pg of soil organic carbon to 1 m deep and 0.5 Pg C/year in sequestration (Lorenz & Lal, 2018; Sha et al., 2022). This storage and sequestration translate to USD 214 trillion in nature's savings account and adds USD 312 billion annually into the savings account, assuming a price of CO_2e at 170 a ton. Bai & Cotrufo (2022) suggests that improving grazing management and biodiversity restoration can achieve a low-cost, high-carbon gain in grasslands worldwide. This study finds the importance of RGS in global climate regulation services and challenges us to rethink their use and maintenance.

Table 1: Global Climate Regulation Services

ESVD2.0_ Biome (No interaction)	**Area (e9 ha)**	**Average (Int$/ha/ year)**	**Median (Int$/ha/ year)**	**# of Values**	**Std Error**	**Min**	**Max**	**Average Value per year (e12 in Int$)**	**Median Value per year (e12 in Int$)**
Earth	51.00	–	–	–	–	–	–	–	–
Marine	36.17	–	–	–	–	–	–	–	–
Marine – Coastal Systems	3.10	15,982	149	64	13,767	3.34	880,239	49.5	0.46
Marine – Open Sea	33.07	93	73	16	32	0.03	484	3.1	2.40
Global Terrestrial Surface	14.83	–	–	–	–	–	–	–	–
Rangelands,	3.50	24,613	473	23	13,321	0.13	258,256	85.7	1.65

ESVD2.0_ Biome (No interaction)	Area (e9 ha)	Average (Int$/ha/year)	Median (Int$/ha/year)	# of Values	Std Error	Min	Max	Average Value per year (e12 in Int$)	Median Value per year (e12 in Int$)
Natural Grasslands, and Savannas									
Intensive Land Use (Croplands)	0.16	7,625	84	91	7,454	0.02	678,475	12.7	0.14
Temperate and Boreal Forests and woodlands	2.48	5,460	230	56	2,370	2.20	78,186	12.4	0.52
Tropical Forests	1.73	712	288	44	169	0.07	5,533	1.2	0.50
Urban and Industrial Areas	0.10	1,455	852	15	650	15.67	10,371	0.1	0.09
Inland Wetlands	1.29	1,136	256	23	479	4.97	9,420	1.4	0.31
Polar – Alpine	0.36	671	809	5	285	1.73	1,314	0.9	1.13
Rivers and Lakes	0.55	355	329	4	195	4.27	758	0.1	0.13
Tundra	1.16	—	—	—	—	—	—	—	—
Antarctica, Greenland Ice sheets	1.57	—	—	—	—	—	—	—	—
Deserts – Barren Land (19% of Terrestrial)	2.82	—	—	—	—	—	—	—	—
Statistical Error	0.27	—	—	—	—	—	—	—	—

Note. Surface area of earth, water and land were obtained from Nations Online Project (n.d.). Rangelands, natural grasslands and savannas including shrublands from the International Livestock Research Institute (2021). Tropical forests from Poker & MacDicken (2016). Total forest area from Food and Agriculture Organization (FAO) of the United Nations (2019). Temperate, boreal and woodlands is estimated at 2.478 billion ha, from the

United Nations Economic Commission for Europe (2000). Surface area of lakes greater than 0.001 ha was 0.476 billion ha obtained from Verpoorter et al. (2014). Allen and Pavelsky (2018) estimated rivers and streams at 0.0773 billion ha. Intensive land use from Tubiello et al. (2021). Urban and industrial area from Gao & O'Neil (2020). Inland wetlands from Davidson et al. (2023). Polar-Alpine from Testolin et al. (2020). Tundra and Deserts – Barren land from International Livestock Research Institute (2021). Tundra and Desserts from International Livestock Research Institute (2023) and United Nations (n.d.). Antarctic and Greenland ice sheets obtained from National Snow and Ice Data Center (n.d.). The statistical error of 0.27 billion ha reflects some double counting and statistical errors.

Figure 3: *A panorama of the Lac du Bois Grasslands Protected Area north of Kamloops, B.C. (Straitgate/Wikimedia Commons).* CC BY-SA 3.0

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How Will the Alberta Oil Sands Affect Future Generations?

ALEXANDER URQUHART

Introduction

Alberta oil sands' success is complicated and often criticized; nonetheless, oil sands are a major part of the Alberta economy and create employment opportunities. This short commentary will investigate how Alberta's oil sands are a ticking time bomb for the province and the country as a whole.

Alberta's Oil Sands

In 2023, Canada produced 5.6% of the world's oil, 80% of which was produced in Alberta's oil sands (U.S. Energy Information Administration, 2023; Canada Oil Production | The industry across Canada., n.d.). Alberta's oil sands make up 21% of the province's yearly GDP and roughly 3% of the national GDP (Government of Canada, 2023; Jones, 2024). According to the Alberta government's website, the oil sands industry emits 70 megatonnes (Mt) of greenhouse gases (GHG) yearly (Ministry of Environment and Protected Areas, n.d.). As of 2021, those emissions are roughly 10% of Canada's yearly GHG, but they are expected to grow by 2030 (Heyes et al., 2018).

Yet oil sands may not exist if not for the Alberta, Ontario and federal governments stepping in with financial support in the 1960s, 80s, and 90s, which can still be seen today with the Kinder Morgan pipeline (Wilt, 2018). In 1995, the Alberta government agreed to a generic royalty regime for the oil sands industry that only charges 1% of revenues until the project has recuperated its capital cost. Since the publicly funded oil sands showed signs of profit, private investment supposedly dominated the industry in the 2000s. Yet public money still finds a way into these projects through grants for innovation, carbon reduction, and transportation.

Figure 1: *Athabasca oil sands (Jesse Allen & Robert Simmon/*NASA *Earth Observatory)* NASA *Media Usage Guidelines*

Oil sands have a return on investment (ROI) of around 4:1 to 7:1 (Canadians for a Sustainable Society, n.d.). For reference, drilling has a return on investment of 25:1.

Oil Sands Emissions

Oil produced from oil sands has also been shown to have much higher emissions than other oil sources. In 2015, the

California Air Resources Board found that Western Canada Select emits 18.43 grams of carbon per megajoule (MJ) of energy used in production. For comparison, North Dakota Bakken crude emits 8.71 grams of carbon per MJ, 47% less than Western Canada Select (Heyes et al., 2018).

Currently, the Pathways Alliance is proposing a carbon capture facility in Northeastern Alberta to reach carbon neutral by 2050 (The Pathways Alliance, n.d.). Carbon capture technology has been criticized for its environmental risk, expense, and infrastructure requirements. Additionally, these facilities capture carbon during production and not after combustion. This effort seems like a great expense, CAD 16.5 billion specifically, that the oil sands industry is once again expecting to be picked up and financially backed by the Alberta government.

Boreal Forests Affected by Oil Sands

Boreal forests account for approximately 20% of global carbon sinks but are highly at risk due to climate change. It is believed that Boreal forests will be affected by an increase in fire disturbance and higher temperatures as climate change progresses (Espinosa-Leal et al., 2019). This belief has implications for the future reclamation of oil sands, which have disturbed 940 thousand hectares, of which 0.1% has been restored and returned to the province (Lothian, 2017).

Currently, there are 95,300 hectares of land leased for oil sand mining, which will eventually need to be reclaimed and restored to functioning ecosystems (EnergyNow Media, 2022). In 2010, it was believed that reclamation would cost approximately CAD 220,000 to 320,000 per hectare in the region, resulting in a minimum cost of CAD 20.7 billion (up to CAD 30.1 billion) (Lemphers et al., 2010). Recently, the Alberta Wilderness Association estimated the cost of reclamation to be CAD 130 billion (Anderson, 2019). The total calculated reclamation costs for the oil sands mining industry was only CAD 27.8 billion, which aligns with Lemphers et al.'s (2010) estimation. In the calculations below, we will assume that reclamation costs will be the average value of approximately CAD 80 billion.

Boreal forests are thought to sequester and store 11 teragrams (Tg) of carbon per year in Canada (Kurz et al., 2013). As the Canadian government rolls out carbon sequestration strategies across the country, tree planting being one, it seems that the 94,095 hectares in Alberta's oil sands would be the perfect place to introduce this strategy. Not only will the area require restoration in the next 30 years, but the area is a large carbon sink that is currently not in use.

Table 1 shows a breakdown of the details and costs of oil sands reclamation.

Table 1: Details & Costs of Oil Sands Reclamation

Reclamation Aspect	**Details**
Oil sand deposits total coverage	14 million hectares
Oil sands leased to companies for extraction	9.3 million hectares
Current land disturbance (2022)	95,300 hectares
Total disturbed area (2020)	65,300 hectares
Total area of tailings lakes (2020)	30,000 hectares
Total volume of tailings (2020)	1.4 trillion liters
Security deposit (2019)	$939 million for environmental protection
Security deposit per hectare of disturbed land	$9,853
Estimated reclamation cost of current disturbance	$27.8 – $130 billion, avg $80 billion
Estimated reclamation cost per hectare	$290,000 – $1.36 million, avg. $840,000
Potential taxpayer liability based on 4 million taxpayers in 2050 from 2.9 million currently	$6,950 to $32,500, avg $20,000 per Alberta taxpayer
Recommendations	public consultation, third-party verification, expansion of liability coverage

Note. All $ amounts in CAD. Information on oil sands is from the Canadian Encyclopedia (Davidson, 2014), EnergyNow Media (2022), Environmental Defence Canada (Chow-Fraser & Rougeot, 2022), Alberta Wilderness Association (Anderson, 2019), and Lemphers (2010).

Media Attribution

Figure 1: "Athabasca Oil Sands" by Jesse Allen and Robert Simmon [using EO-1 ALI data courtesy of the NASA EO-1

team. Caption by Holli Riebeek] (2009), via NASA Earth Observatory, is used under the NASA Media Usage Guidelines.

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CLIMATE CHANGE ADAPTATION & MITIGATION STRATEGIES

Climate Change, Inequality, & Indigenous Communities in Canada

MEGHAN ALLAN AND MOLLY SLADDEN

Introduction

Climate change is already having major impacts on the entire global economy, but Indigenous peoples are disproportionately affected despite their low contributions to global GHG emissions (Alexander et al., 2011). This results in negative effects on their opportunities to exercise their constitutional rights, including but not limited to cultural, social, political, and economic inherent rights (Lynn et al., 2011; Redvers et al., 2023). In this short commentary, we will summarize some of these major impacts and focus on the economics of these impacts on Indigenous communities.

Economical Impacts on Indigenous Communities

Food & Water

Indigenous peoples in Canada are known to experience inflated levels of poverty. The average income of an Indigenous person is 25% less than the average Canadian's income, and the average income of an Indigenous person living on a reserve is 50% less (Hillel 2020). This decreased economic power, due to historical and continuous colonial institutions, already exposes Indigenous peoples to additional climate change risk (Brittain & Blackstock, 2015; United Nations, General Assembly, Third Committee, 2022). Furthermore, despite Canada having the third largest stock of freshwater in the world, Indigenous communities have unduly low access to clean drinking water (The World Bank 2020; Government of Canada, 2024). For example, about 70% of First Nations in Ontario had at least one drinking water advisory between 2004 and 2013 (Lucier et al., 2020). Water scarcity is predicted to increase with climate change, potentially aggravating this pivotal concern despite Government efforts (Baggio et al., 2021; Bhargava & Bhargava, 2023; Government of Canada, 2024; White et al., 2012).

Land

Figure 1: *Include women and Indigenous people in the fight against the climate crisis* (Roberta Scalise/Open Democracy) CC BY-NC 4.0

Additionally, Indigenous peoples in Canada tend to have an enhanced relationship with the land, and while they have shown tremendous resilience and adaptation to disruption and changes in the land base, the exponential increase in these changes also increases their climate change risk (Ford et al., 2020; Johnston & Spring, 2021; Lynn et al., 2011; Zavaleta-Cortijo et al., 2020). For example, fisheries are a foundational resource to Indigenous peoples in B.C., but fisheries are predicted to experience declines between 15% to 28% (depending on RCP pathways) due to increasing temperatures, ocean acidification, and drought (First Nations Fisheries Council of British Columbia, n.d.). Most research has concentrated on the economic impacts of large-scale fisheries, but this will also result in lower food and economic security, especially for subsistence-based communities (Weatherdon et al., 2016). Moreover, northern Indigenous communities are at higher risk of food insecurity due to magnified warming effects and reliance on the land (Johnston & Spring, 2021).

Natural Disasters

Meanwhile, economic opportunities are lost while trying to mitigate natural disasters related to climate change, as these events are often unpredictable. During the 2017 'Mega' Wildfires, the Bonaparte Band spent over $600,000, and the Nadleh Whut'en First Nation spent $400,000 on wildfire equipment and operations within their Bands' territory (Dickson-Hoyle and John 2021; Kane, 2018). Additionally, Bonaparte relies on the forestry industry for economic gain and opportunity and felt major losses post-wildfire due to damage and tree mortality. On top of that, they spent tens of thousands of dollars rehabilitating a burnt archeology site (Dickson-Hoyle & John, 2021). The small town of Lytton burnt to the ground in 2021, destroying 90% of the structures; almost two years later, rebuilding was still causing economic strain among many community members (Partlow, 2022). Additionally, it was found that almost $27,946,030 was the direct cost of the decimation of Lytton and that 38% of business owners have had no revenue since the fire (see **Table 1**) (O'Leary and Associates, 2023).

First Nation communities are heavily impacted by climate-change-related events, specifically wildfire activities. In 2023 alone, more than 42% of evacuations due to wildfire were from predominately Indigenous communities (Webber & Berger, 2021). Indigenous Peoples have used traditional food systems since time immemorial, fulfilling an integral way of life and well-being as they provide cultural, spiritual, and physical needs (Redvers et al., 2023). Food systems and traditional medicines have been greatly impacted by climate change and its related effects, resulting in food insecurity and uncertainty for many Indigenous Peoples and their communities. Communities have spoken out post-fire, voicing their concerns about their traditional harvesting and hunting grounds (Dickson-Hoyle & John, 2021; McKay, 2023).

Table 1: Impact of Wildfire on Business Revenues in Lytton & Region — Survey Response Distribution

Revenue Change	**Responses (%)**
My business has had no revenue since the wildfire	38
0% to 9% lower	19
10% to 24% lower	25
25% to 49% lower	6
50% to 74% lower	6
Greater than 75% lower	6

Note. Data from pie charts created by O'Leary and Associates Ltd. (2023).

Conclusion

The economics of climate change's impact on Indigenous peoples in Canada requires an increase in data collection and research; however, it is evident that they will be disproportionately affected. Further investigation and solutions must be done in collaboration with Indigenous people and their traditional knowledge, which has already been paramount in adapting to climatic changes (Alexander et al., 2011; Johnston & Spring, 2021). Larissa Crawford put it best in her interview with the Pembina Institute (2022): "The physical consequences of environment and climate change cannot be removed from the social and political implications and causes. Climate justice means that climate action done on any of the globe's Indigenous lands must centre Indigenous peoples' knowledge systems and sovereignty."

Media Attributions

Figure 1: "Include women and Indigenous people in the fight against the climate crisis" by Roberta Scalise (2021), via Open Democracy, is used under a CC BY-NC 4.0 license.

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Precision Agriculture: Navigating Climate Change Challenges for Sustainable & Profitable Farming

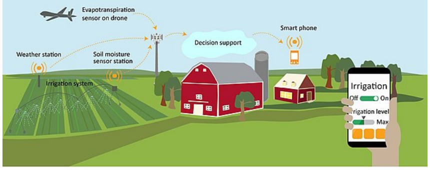
ALEXANDRE CROTEAU AND ALICIA GUAY

Introduction

Rising temperatures, altered precipitation patterns, and increased extreme weather events due to climate change pose significant threats to agriculture by impacting crop yields, water resources, and overall sustainability (Intergovernmental Panel on Climate Change [IPCC], 2022). This scenario complicates global food security efforts and stresses agricultural systems. The situation is aggravated by the projected 50% increase in food production demand by 2050, driven by population growth and the rising need for biofuels (Medel-Jiménez et al., 2023). GHG emissions from agricultural production emitted 9.3 Gt CO_2eq in 2018 (Food and Agriculture Organization of the United Nations [FAO], 2020). Against this backdrop, transformative precision agriculture (PA) technologies, including variable-rate technology (VRT), guidance systems (GS), and geographic information system

(GPS) mapping, as well as other emerging technologies such as artificial intelligence (AI) and remote sensing (RS), offer viable solutions to climate change challenges. This commentary explores the economic implications of these technologies globally and in the Canadian context.

Precision Agriculture



Source: GAO. | GAO-20-128SP

Figure 1: *Components of a precision agriculture system (U.S. Government Accountability Office).* *GAO Terms of Use*

Economic Implications

PA uses GPS, sensors, and data analytics to enhance farming practices, boosting productivity, reducing environmental impacts, and mitigating GHG emissions (Balfoutis et al., 2017). These technologies enhance management practices, reduce costs, and improve yield outcomes, presenting substantial economic benefits for the agricultural sector. A study published by Schimmelpfenning (2016) found that adopting PA technologies could lead to a noticeable increase in profit margins for farmers, although the magnitude of benefits could vary by crop and technology. According to the summary report of Schimmelpfenning (2016), the adoption of PA technologies has a small positive impact on both net returns (including overhead expenses) and operating profits for a U.S. corn farm of average size (see **Figure 2**).

Specifically, GPS mapping shows the largest estimated impact among PA technologies, with an increase in operating profit of almost 3% on corn farms.

Beyond individual profit margins, PA contributes to broader economic benefits by enhancing sustainability, reducing environmental impacts through more efficient use of inputs, and contributing to food security by increasing production efficiency (Nicol & Nicol, 2018). However, the initial investment in PA can be significant. This investment includes the cost of hardware (GPS devices, sensors, drones and automated machinery) and software (data analysis and management).

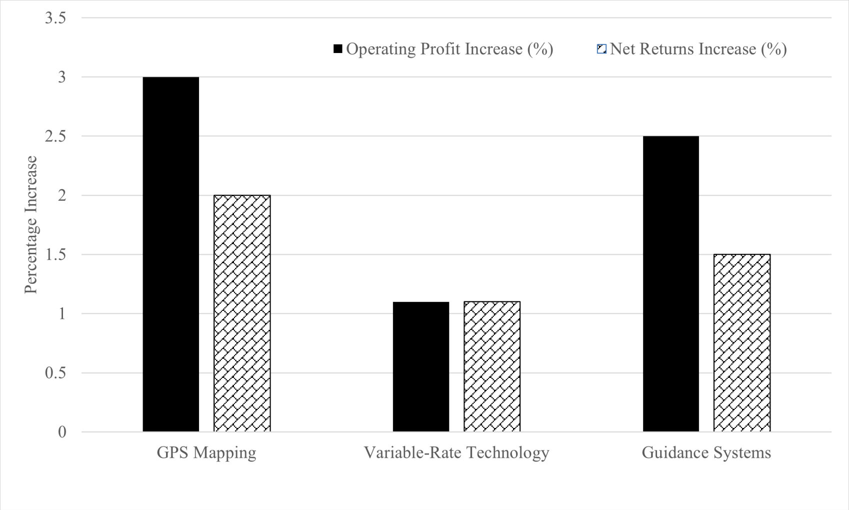


Figure 2**:** *Comparative impact of precision agriculture technologies on U.S. Corn Farms. Data for this analysis originate from the Schimmelpfennig* (2016) *summary report, utilizing U.S. field crop production data from* 1996 *to* 2013 *provided by the Agricultural Resource Management Survey* (ARMS), *a collaborative effort between the USDA's National Agricultural Statistics Service* (NASS) *and the Economic Research Service* (ERS). CC BY-NC-SA 4.0.

Canadian Agricultural Landscape

In 2022, Canada's agricultural sector, which contributed 8.1% to the country's total GHG emissions, employed 249,900 people and generated $36.3 billion, accounting for approximately 1.8% of the GDP (Environment and Climate Change Canada, 2023; Agriculture and Agri-Food Canada, 2023). The 2021 Census of Agriculture in Canada highlights the growing adoption of PA technologies, such as GIS mapping, slow-release fertilizers, and drones, indicating a shift toward more efficient and sustainable practices. For instance, GIS mapping increased on Canadian farms from 8.2% in 2015 to 13.2% in 2020, allowing for detailed crop cultivation data collection and optimized yield planning (Chen & Jewitt, 2023).

Other Transformative Technologies

The AI agriculture market, which stood at $1,254.6 million, is projected to expand by 26.7% from 2022 to 2030, reaching $8,308.5 million (Sakapaji & Puthenkalam, 2023). AI improves crop management, reduces pest and disease losses, optimizes resource use, and increases yields (Ampatzidis, 2018; Ennouri et al., 2021). Meanwhile, RS technology facilitates efficient crop health and environmental condition monitoring, enabling timely risk mitigation (Ennouri et al., 2021; Vidican et al., 2023).

Challenges to Adoption & Policy Recommendations

Despite their benefits, adopting these technologies faces challenges, including high initial costs, a lack of technical expertise, and data privacy concerns (Mitchell et al., 2020; Nicol & Nicol, 2018; Sakapaji & Puthenkalam, 2023). Government policies and initiatives, such as subsidies, tax incentives, and investments in research and development, are essential to facilitate adoption. These measures can help overcome adoption barriers, paving the way for a more sustainable and productive agricultural future.

Media Attributions

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Is There Enough Time to Limit Warming to 2°C? The Cost & Speed of a Renewable Energy Transition

ADRIA HUSER

Introduction

At the current rate of global emissions and warming, temperatures are expected to surpass 2°C above pre-industrial levels within this century (Intergovernmental Panel on Climate Change [IPCC], 2018). This short commentary explores the costs and speed of a renewable energy transition that can limit warming from reaching 1.5-2°C. The transformations to achieve this are similar to what is needed for 2°C (IPCC, 2018). As the majority of literature focuses on a 1.5°C limit, this commentary will reflect that, with the idea of 2°C being avoided in the same measures.

***Figure 1**: Danish wind turbines (Leonard G/Wikimedia Commons).* CC BY-SA 1.0

Transitioning to Renewable Energy

The 2015 Paris Agreement involved a pledge to limit global warming to well below 2°C relative to pre-industrial temperatures. Despite this agreement, Welsby et al. (2021) found that fossil fuels remain the dominant energy system. To limit warming to 1.5°C by 2050, a decline in fossil fuel use and extraction must take place, meaning nearly 60% of oil/fossil methane gas and 90% of coal sources must remain unextracted. Increasing the use of renewable energy worldwide will likely reduce CO_2 emissions associated with fossil fuels. Renewable energy (e.g., wind, solar, and geothermal) is sustainable, nonpolluting, and found everywhere in the world; it is an important element of a low greenhouse gas energy economy and a feasible alternative to the fossil-fuel-based energy systems used today ((Nelson & Starcher, 2019).

Economic Benefits

Jacobson et al. (2017) assessed 139 countries' transition to renewable energy and determined that, if we continued with the systems we operate on today, the net global-warming-caused damages are estimated to be $28.5 trillion/year by 2050. Business as usual (BAU) energy systems (fossil fuel systems) have total capital costs of ~$2.7 million/MW; wind, water, and solar (WWS) energy systems have a total capital cost of ~$2.5 million/MW (see **Table 1**) (Jacobson et al., 2017). The shift from BAU to WWS also involves the avoidance of the social costs of global warming (e.g., costs due to flooding, real-estate damage, agricultural loss, health problems, and wildfires) and the creation of ~24.3 million net new permanent, full-time jobs (Jacobson et al., 2017).

Table 1: Total Capital Cost of Renewable Energy vs. Fossil Fuels

Energy Source	**Capital Cost (MW)**
Renewable energy (wind and solar)	2.5 million
Business as usual energy systems (fossil fuels)	2.7 million

Note. Total capital costs of wind, water, and solar energies (WWS) is compared with the total capital cost of the business as usual (BAU) energy sources such as oil and fossil fuels are compared as well for 2050 (IRENA, 2023).

Wind & Solar Energy

Of the many renewable energy sources, Usher (2019) states that wind and solar energy are the most cost-competitive with BAU energy sources. Wind energy is produced by wind turbines both onshore and offshore, with offshore wind projects experiencing more electricity generated due to steadier wind speeds. Wind energy expenses include the construction of the turbines (the cost of steel) and operating costs (e.g., leasing land and operating projects), with maintenance being the highest cost. The problem with wind energy is that it is considered intermittent, as electricity is only produced when the wind is blowing (Usher, 2019). This problem is where solar energy comes in; when the wind is not blowing, sun energy can be collected. The raw materials needed to produce electricity from light are abundant and inexpensive, and while manufacturing is more costly, there are few operating costs once the panels are installed (Usher, 2019). The costs associated with both wind and solar energy are summarized in **Table 2**.

As of 2022, the total installation costs of wind energy (both offshore and onshore) amount to USD 4,735/kW, with a levelized cost of energy (LCOE) amounting to USD 0.11/kWh; the total installation cost of solar energy in 2022 was USD 876/kW, and the LCOE was USD 0.05/kWh for solar photovoltaic energy (International Renewable Energy Agency [IRENA], 2023). Capital costs of wind and solar energy sources are compared with the costs of fossil fuel energy sources in **Table 2**. The electricity needed for a 100% shift to wind and solar power sources by 2050 is noted as well, with solar voltaic energy requiring the most energy of the three at 6.81 TW ("Cost of electricity by source," 2024).

Table 2: Renewable Energy — Total Costs of Electricity (2022) & Electricity Needed to Shift by 2050

Energy Source	Capital Costs (USD/kW)	Levelized Cost of Electricity (USD/kWh)	Total Installed Cost (USD/kW)	Electricity Needed For a 100% Shift by 2050 (TW)
Offshore wind	3,285–5,908	0.08	3,461	1.61
Onshore wind	1,462	0.03	1,274	2.79
Solar photovoltaic	1,333–2,743	0.05	876	6.81
Coal power	3,075–5,542	–	–	–
Natural gas	922–2,630	–	–	–

Note. Capital cost estimates for renewable energy technologies are compared to fossil fuel costs (coal, gas) in the first column ("Cost of electricity by source," 2024).

Conclusion

The transition from fossil fuels to renewables will be critical in avoiding the devastating effects of climate change. Prices of wind and solar energy sources have fallen significantly since 2010 (IRENA, 2023), becoming more competitive with the prices of BAU energy sources each year. Studies have established that this transition may be feasible technically and economically; however, social and political systems are the biggest barriers (Jacobson et al., 2017).

Media Attribution

Figure 1: “DanishWindTurbines” by Leonard G (2004), via Wikimedia Commons, is used under a CC BY-SA 1.0 license.

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The Economic Implications of Rising Sea Levels for Coastal Cities & Adaptation Strategies

ELLA LINDSAY AND EMMA CHRETIEN

Introduction

This commentary will discuss the costs coastal cities face because of sea level rise and how adaptation or mitigation might help.

Economic Impact of Rising Sea Levels

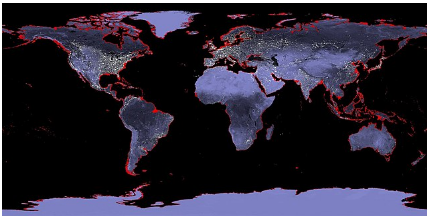

***Figure 1**: 6 m sea level rise* (NASA) *Public Domain*

Sea levels increase because glaciers and polar ice caps are melting due to rising global temperatures. Both economies and coastal infrastructure are at risk. “During the 20th century, a significant acceleration of sea-level rise has occurred, quantified at about 1.2 mm per year from 1901 to 1990… the period 1993–2010 revealed a much larger acceleration, of about three millimeters per year" (Abadie et al., 2020). The economic impact of sea-level rise on coastal cities is multifaceted.

Firstly, the rising sea levels cause direct damage to buildings, roads, and utilities. Ralls (2024) reports, "a recent study has unveiled alarming projections for world economies, with estimated losses reaching well over $1 trillion by the century's end due to the impact of rising sea levels on coastal cities". Roads, bridges, and ports are the costliest repairs at risk from rising sea levels; these areas of infrastructure make up the majority of the estimated $1 trillion spent by the end of the century (Ralls, 2024).

Aside from the cost to repair infrastructure, there are also the costs associated with long-term economic consequences. It is common that coastal cities, especially in North America, have large amounts of tourism that contribute significantly to the national GDP. Additional costs come from adapting these coastal cities to protect them from sea level rise, such as building seawalls and updating drainage systems. In Europe, nearly 30% of the population "resides in a 50 km strip of the coast, where many ecosystems, assets and infrastructures are located" (Abadie et al., 2020), which proves to be problematic for these coastal cities as rising sea levels has been a growing concern due to socioeconomic factors in the past, climate change is expected to make this situation much worse in the future. Rising sea levels in Europe are a pressing issue, "extreme events may cause severe economic impacts. With no additional investments in adaptation, global damage due to coastal flooding could reach between 93,000 and 961,000 million euros" (Abadie et al., 2020). There must be preventative measures put in place.

Adapting to Rising Sea Levels

Rising sea levels cause increasing costs for coastal cities, so it is necessary to adapt to these impacts if the adaptation is less costly than the future damages. Coastal areas are also some of the most populated places on Earth (Brown et al., 2018). Reducing the harsh economic effects requires adaptation techniques, including protecting land from sea-level rise. Hinkel et al. (2014) report that the global costs to use and maintain dikes to prevent coasts are USD 12–71 billion in 2100, which is still significantly less than the total cost of avoided damages (Hinkel et al., 2014). Neumann et al. (2015) declare that adaptation is the most cost-effective measure as well. This displays that adapting to sea-level rise due to climate change can help lower the future economic implications for cities on coastlines. The technique used for adaptation is important, as Hinkel et al. (2014) note that it is important to estimate the costs of coastal flooding to determine appropriate adaptation strategies as well as account for uncertainties of socioeconomic development. See **Table 1** for a summary.

Table 1: Research on Costs of Sea Level Rising

Source	**Key Points**	**Economic Impact**	**Adaptation Costs**
Ralls (2023) **Abadie, Murieta, & Galarraga (2020)**	Estimated losses over $1 trillion by century's end due to sea-level impact on coastal cities.	Direct damage to infrastructure (roads, bridges, ports).	—
Hinkel et al. (2014)	Costs of using and maintaining dikes	Avoided damages are significantly higher than adaptation costs.	USD $12–71 billion by 2100

Assessing Mitigation & Non-Mitigation Scenarios

Brown et al. (2018) assess the impacts of mitigation and non-mitigation scenarios on flood plain areas. They analyze the sea-level rise and coastal floodplain areas, finding that mitigation can help reduce projected floodplain areas, and the difference between mitigation and non-mitigation for floodplain areas is greatest in 2300 (Brown et al., 2018). Brown et al. found that the floodplain in 2000 was 54 million hectares. In the future, the floodplain will be about 62.5 million hectares under mitigation in 2100 and 163 million hectares under no mitigation in 2300, which is a larger difference than in 2000-2100 (see **Table 2**) (Brown et al., 2018). However, Brown et al. (2018) report that even if we do reduce GHGs and slow temperature rise, sea levels will still slowly increase well into the future, which is why adaptation is so important as well.

Table 2: Impact on Flood Plain Under Different Scenarios.

Year	**Scenario**	**Flood Plain Area (millions of ha)**	**Population Exposure (%)**
2000	Baseline	54	–
2100	Mitigation (Median)	62.5 (5th and 95th percentile: 58-70)	–
2300	Mitigation (Median)	78.5 (5th and 95th percentile: 61-129)	1.5–5.4
2300	Non-mitigation	163 (5th and 95th percentile: 119-222)	1.2–7.6

Note. Population exposure percentages for 2300 assume no population growth after 2100 (Brown et al., 2018).

Conclusion

Overall, this short commentary finds that the economic damage caused by rising sea levels is extensive, and rising sea levels will also have major implications for floodplain areas. Many people will be affected if no mitigation or adaptation strategies are adopted. Policies and protective measures must be put in place before the damage to coastal cities is irreversible, therefore making them unlivable.

Media Attribution

Figure 1: "6 m sea level rise" by NASA (2012), via Wikimedia Commons, is in the public domain.

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Coastal Adaptation Measures in the Aquitaine Region of Southern France

DIPIKA POPATLAL

Introduction

This commentary will focus on the Aquitaine region in Southern France. Specifically, what can be done to mitigate the losses from climate change and if there are any risks and benefits to this process. The Aquitaine region is most widely affected by erosion and coastal flooding risks, with the coastline already showing signs of retreatment (Baills et al., 2020). Rising sea levels would widen the Gironde Estuary. Bordeaux, with a 262,000 population, will be dramatically affected as there will be a loss of land. Libourne will also be affected as the Dordogne and Garonne riverbeds expand. The Arcachon Bay area will be flooded. **Figure 1** illustrates these impacts on the coastal region.

Adapting to Coastal Hazards Caused by Climate Change

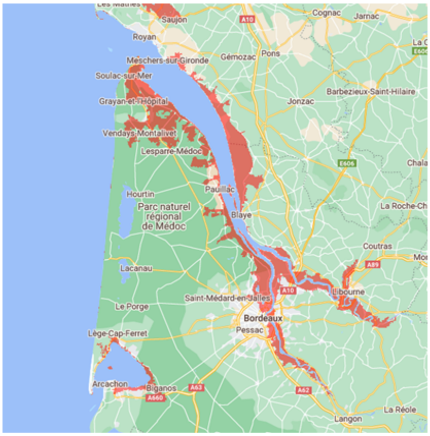
Figure 1: *Land projected to be below annual flood level in 2100 (Climate Central). Climate Central Terms of Use*

This commentary will explore two potential strategies that aim to adapt to the impacts of climate change, with a specific focus on coastal hazards. The first option involves the observation and study of natural evolution, while the second option involves actively controlling and directing natural processes. Both measures are necessary to address changes in sea levels (Smit & Wandel, 2006).

Monitoring natural processes entails observing areas devoid of human intervention to comprehend erosion and flooding. This involves utilizing coastal monitoring tools to collect data on physical processes, aiding in the anticipation of future alterations and potential adjustments in management strategies. Managing natural processes is crucial for mitigating erosion in coastal ecosystems, including dunes, marshes, and cliffs. For example, on the sandy coast of Aquitaine, this could entail practices such as vegetation planting or employing ecological techniques to stabilize sand

and mitigate wind erosion (Baills et al., 2020). Nevertheless, implementing measures may also yield adverse consequences. An example commonly involves a defensive structure situated along the shoreline. The main objective of this structure is to reduce coastal flooding and prevent erosion along the coastline. However, it unintentionally causes increased erosion at both ends and the base of the structure (Baills et al., 2020).

Overall, numerous options for adapting in the near and moderate future (2030–2050 and 2080–2100) can be implemented. Emphasis should be given to proactive planning for adaptation, especially when there is a time lag between implementing a measure and seeing its anticipated advantages. This method emphasizes finding solutions (adaptation measures), which simplifies decision-making amid unpredictable changes in risks (Berrang-Ford et al., 2011). **Table 1** summarises the impacts.

Table 1: Impact From Sea Level Rising & Measures

Aspect	**Details**
Location	Bordeaux area, including the Gironde Estuary, Libourne, and Arcachon Bay, France.
Climate change impacts	• Gironde Estuary to widen • Libourne at risk from expanding Dordogne and Garonne rivers • Arcachon Bay may face flooding.
Adaptation strategies	Focus on flood defenses, land use management, and ecological restoration to protect against increased water flow and sea levels.

Coastal and river management approaches	• water flow management in rivers and estuary • ecological solutions like wetland restoration • urban planning adaptations for resilience.
Risks of intervention	Infrastructure may impact ecology; protective measures could shift flood risks.
Community and stakeholder involvement	Collaboration among governments, communities, and organizations for effective adaptation.
Conclusion	The Bordeaux area requires integrated strategies for climate change adaptation, emphasizing structural, ecological, and community approaches.

Note. Data from Baills et al. (2020), Berrang-Ford et al. (2011), and Smit & Wandel (2006).

Conclusion

In conclusion, whichever method to use will highly depend on how climate change has affected this area. In this area of France, the development of these adaptation pathways needs to be based on detailed hazard projections to maintain the life expectancy of these measures.

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Figure 1: "Land projected to be below annual flood level in 2100" [generated by Coastal Risk Screening Tool: Land Projected to be Below Annual Flood Level in 2100] by Climate Central (n.d.) is used under the Climate Central Terms of Use.

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Navigating the Waves: Analyzing Climate Change Impacts on Global Fisheries & Socioeconomic Resilience

ANDRES STREET AND LUBO MAGDOLEN

Introduction

This short commentary will analyze the effects of climate change on global fisheries. With the evidential threat of climate change on global fisheries, it is essential to understand the impacts and cumulative effects climate change will have on fisheries around the globe. The objective is to outline the impacts of climate change on changing fish stocks, distribution patterns and communities that rely on fish as an essential food source and a way to make a living. It is important to understand the socioeconomic contribution of global fisheries to human society as the fishing sector itself provides more than 3 billion people with 20% of their average annual per capita protein intake and generates global revenues above USD 100 billion annually (Talloni-Álvarez et al., 2019).

Impact of Climate Change on Fisheries

***Figure 1**: Fish diversity (The0Quester/Wikimedia Commons). CC0 1.0 Universal*

Fish Stocks Moving North

Climate change has significantly altered the resiliency and stability of transboundary fish stocks in Canada and USA (University of British Columbia, 2022). As ocean temperatures rise, certain models have been shown to predict the migration of various species into high-latitude regions, specifically the Arctic and the Southern Ocean (Cheung et al., 2009). Regions that will potentially be affected the most are Canada and the United States below latitude 43 (University of British Columbia, 2022). As ecological communities change and alter with the warming of oceans, countries must shift management strategies and share information as species distribution shifts North due to warming southern waters (Palacios-Abrantes, 2023). As fish stocks move north due to climate change, the impacts on the tropics are predicted to be the highest, and maximum catch potential (MCP) and maximum revenue potential are expected to decrease by 38% and 33%, respectively, while the exclusive economic zones (EEZ) is expecting tropical fisheries MCP to decline by 80%

As climate change is affecting tropical fisheries, there will be positive impacts on more northern countries (Lam et al., 2016). Regions higher than 75°N and Northern Atlantic regions greater than 70°N are expected to have an increase in maximum revenue potential (MRP) of 71% to 100%.

Economic Challenges

The economies of fisheries in dependent countries are increasingly facing the impacts of climate change, posing significant challenges to the well-being of coastal, riverine, and island nations (Food and Agriculture Organization of the United Nations [FAO], 2018). Rising sea temperatures, ocean acidification, and extreme weather events disrupt marine ecosystems and fish habitats, affecting fish stocks and biodiversity (Intergovernmental Panel on Climate Change [IPCC], 2019). These changes threaten the livelihoods of millions of people who depend on fisheries and aquaculture for sustenance and income (FAO, 2018). It is shown that with rising CO_2 emissions, 2050 revenues could drop by more than 35% than the projected decrease in catches (Lam et al., 2016).

Shifts in the distribution and abundance of fish species due to warming waters are altering traditional fishing patterns and challenging the adaptive capacities of fishing communities

(Cheung et al., 2016). Research indicates that approximately 43.5 million individuals are currently employed in fisheries and aquaculture worldwide, with a significant majority (90%) working as small-scale fishers. Additionally, it is believed that over 200 million people, primarily in developing nations, rely on small-scale fishing for their livelihoods (Mohanty et al., 2010). Extreme weather events such as storms and cyclones can cause damage to fishing infrastructure and vessels, further exacerbating the vulnerability of dependent economies (IPCC, 2019). Climate change impacts on fisheries have far-reaching consequences, including reduced catches, loss of income, and increased food insecurity, highlighting the urgent need for adaptation measures and international cooperation to support the resilience of fisheries-dependent nations.

Table 1 summarizes the impacts on global fisheries in the North and the South.

Table 1: Summary of Impacts in the North and South

Events	**Impact in the North**	**Impact in the South**
Migration of Fish Stocks	Species migrating into Arctic and Southern Ocean. Regions higher than 75°N and Northern Atlantic > 70°N see increased fish stocks.	Major losses below latitude 43, particularly in the tropics. Declines in fish stocks due to warming southern waters.
Economic Impacts	MRP increase of 71% to 100% in regions higher than 75°N and Northern Atlantic >70°N.	MCP and revenue potential decline by 38% and 33% respectively. Tropical EEZ fisheries MCP expected to decline by 80%.
Employment	Increased employment and improved	Significant risk to the livelihoods of

and Livelihoods	livelihoods in northern regions due to higher fish stocks.	small-scale fishers and those reliant on fishing, particularly in developing nations.
Environmental and Climate Impacts	Opportunities for new fishing patterns and stocks, yet challenges in adapting to rapid changes and managing new stocks sustainably.	Increased vulnerability to climate change effects like rising sea temperatures, ocean acidification, and extreme weather events.
Adaptive Measures Required	Need for new management strategies, sustainable practices, and information sharing to handle increased fish stocks.	Urgent adaptation measures required to mitigate reduced catches, loss of income, and increased food insecurity.

Note. Data from Cheung et al. (2009), FAO (2018), IPCC (2019), Lam et al. (2016), Mohanty et al. (2010), Palacios-Abrantes (2023), Talloni-Álvarez et al. (2019), and University of British Columbia (2022)

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Soil Degradation & Mitigation Techniques: A Means to Economic Success

ALISON WATERHOUSE

Introduction

In this commentary, the economic loss due to soil degradation is explored. With climate change causing more frequent and severe droughts, there is an increased risk of instability within agriculture production. Managing soil and soil water is vital within the agriculture industry to ensure the highest revenue. Soil loss would result in reduced land productivity, food security, water retention, and biodiversity (Xiong et al., 2018). One of the main causes of soil loss is erosion. Erosion is increased with prolonged dry periods followed by extreme rainfall events (Sartori et al., 2019). Due to the climate change crisis, there is an expected increase in these effects. Moreover, water erosion can increase global warming as the oxidization of soil carbon can release CO_2 (Chen et al., 2017).

Soil Degradation Mitigation Techniques

Figure 1: A *tilled farm* (PxHere). CC0 1.0

Humans also play a direct role in soil degradation due to deforestation, land use change, and agricultural practices (Sartori et al. 2019). In 2007, these actions caused an estimated cost of USD 231 billion annually, determined using a total economic value approach (Nkonya et al., 2015). This value would increase over time as climate change effects and increased land use change are ongoing issues. Soil conservation techniques (SCT) were evaluated to minimize the cost of soil degradation (Xiong et al. 2018). Biological techniques (BTs), soil management techniques (STs) and engineering techniques (ETs) were assessed to determine which provided the greatest reduction in soil loss and water runoff (Xiong et al., 2018).

Biological

One BT to soil degradation is to "cover crops," which utilizes plant cover to retain soil and water. (Xiong et al. 2018; Buendia et al., 2016). Crop cover helps increase organic matter on site, which increases water storage (Li et al., 2023). With various crops assessed, it was found that crop cover reduces soil erosion by 30% to 53% and will reduce water runoff by 33% to 60% (Li et al., 2023).

Soil Management

The ST parameter being assessed was altering soil management by not tilling (Xiong et al., 2018; Keesstra et al., 2016). Not tilling the land is beneficial as tillage results in exposed soil, which is more prone to erosion and water runoff (Keesstra et al., 2016). In the study, soil erosion rates were 0.02 Mg ha− 1 h− 1 in untilled fields and 0.51 Mg ha− 1 h− 1 in tilled fields (Keesstra et al., 2016). Furthermore, there was higher soil moisture within untilled plots than tilled plots (4.44% and 3.47%, respectively). This indicated that untilled plots had less water runoff and more water retention. (Keesstra et al., 2016).

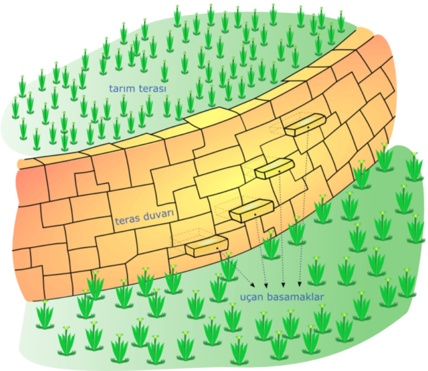

Figure 2: *Inca terracing (Manco Capac/Wikimedia Commons)* CC BY-SA 3.0

Engineering

Terracing was the ET that was evaluated. Terracing is the use of levelled and tiered land while on a slope. When assessed in China, terracing decreased sediment loss by 53.0% and runoff by 48.9% (Chen et al., 2017).

Summary

To better understand the SCT's effect on sediment and water runoff and the cost of implementation, data was compiled and summarized in **Table 1** (Xiong et al., 2018).

Table 1: Comparing Techniques for Reducing Soil Erosion

Techniques	Description of Methods	Reduction in Soil Loss (%)	Reduction in Water Runoff	Perceived Benefit of Crop Production	Estimated Direct Cost of Technique/ ha	What This Means
Biological Techniques (BTs) — Cover Crop	Cover crops are planted to cover soil rather than be harvested. Soil nitrogen can be restored with legumes and other crops. Cover crops reduce erosion and allow water to penetrate the soil.	30–53	33–60	+27	$20.64–$27.40	Hairy Vetch seed and sowing and planting expenses were used to determine crop cover costs. The study assumed no fertilization and ignored application and labour costs.
Soil Management Techniques (STs) — No Till	No tilling is the practice of not tilling one's land before or	59	48	-5.1	$0	The least expensive approach was leaving the land

	after harvesting of crops. Not tilling the land means there is less exposure of bare mineral soil and more retention of organic matter on site.					alone and letting winter weeds grow. There were no fees for tillage, cover crop seeding or herbicide use. It is unclear if not tilling the land boosts or decreases agricultural productivity, depending on location and crop choice. No tilling may impair crop productivity owing to compaction, nutritional deficits, and low soil temperature.
Engineering Techniques (ETs) — Terracing	Terracing is leveling of a sloped land to create elevated tiers of landscape. The leveled tiers increase soil retention and decrease water runoff when compared to the graded slope.	86	44	85.3	$340,666	Terraced plots have slightly better gross margins. Terracing the ground became lucrative and increased crop output when the Cost-Benefit Analysis used 50% of the market price for labour and manure. Terracing increases soil and water retention and makes financial sense.
Overall Soil Conservation Techniques (SCTs) — BTs, STs, and ETs	A combination of BTs, STs, and ETs, that includes crop cover, no tilling,	84	53	N/A	N/A	Crop productivity and technique cost per hectare were not estimated

	terracing, and other soil preservation techniques.					because these metrics vary depending on what BT, ST, and ET is used and where. Overall, combining the three methods reduces soil loss and water runoff best.

Note. The assessment of different soil management techniques and their effects on soil loss, water runoff, crop production and the cost of implementation of such techniques. The BTs reduction in soil and water loss was obtained from Li et al. (2023). The estimated crop production for BT was derived from van Eerd et al. (2023) and was in reference only to legume crop cover. The estimated cost of BTs was calculated only for hairy vetch seed and did not include the cost of labour and application (Bergtold et al., 2017). The soil and water loss of STs, ETs, and overall soil conservation techniques were acquired from Xiong et al. (2018). The decrease of -5.1% of crop production was found from Pittelkow et al. (2015) and the cost of STs was taken from Jacobs et al. (2022). ETs crop production and cost/ha were obtained from Bizoza and de Graaff (2010).

Conclusion

Soil degradation is a direct result of erosion and is an increasing threat because of climate change's effects on weather. Therefore, all SCT methods should be implemented at a higher rate to best combat soil degradation. ETs, like terracing, have the highest potential to reduce soil loss and water runoff, but at a high cost. In contrast, STs, like no tilling, are the cheapest practice but can have the lowest results for reducing soil and water loss with lower crop production. BTs, such as crop cover, can have a high reduction in soil erosion and water runoff while being financially attainable. BTs should be the most applied technique to prevent soil degradation and increase crop production.

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Can We Mitigate the Costs of Flood Damage Through Wetlands?

KYRA WILLIAMSON

Introduction

It is unequivocal that human beings have changed the climate (Intergovernmental Panel on Climate Change [IPCC], 2021). These changes have caused an increase in the frequency and intensity of weather extremes, including heavy precipitation events (IPCC, 2022). Heavy precipitation events and floods cause damage to homes, infrastructure, and the livelihood of individuals within impacted communities (IPCC, 2022). Reducing the effects of floods is crucial to adapting to the changing climate and reducing current and future suffering.

Wetlands are environmental sponges and can be used to prevent flooding. They have the ability to absorb water in times of flooding and slowly release it in times of drought (United States Environmental Protection Agency [EPA], 2001). If we had more wetlands on the landscape and near our communities flooding and the damage it causes, could be reduced. The possibility of using wetlands for this purpose poses two main questions: how do we get more wetlands, and is it economically viable?

Figure 1: *Pond and wetland at Albert McGowan Park. (Arwinddeep Kaur/Tsigaris, et al.,* 2022) CC BY-NC-SA 4.0

Wetland Restoration

Fixing Pre-Existing Wetlands

Figure 2: *Pond and wetland at Albert McGowan Park photo (Tsigaris,* 2024) CC BY-NC-SA 4.0

Increasing how many wetlands we have on the landscape and near our communities, has a simple solution: fix the pre-existing wetlands that have been degraded. Roughly 35% of the world's wetlands were lost from 1970 to 2015 and the destruction of wetlands has only increased in the 2000s (United Nations Climate Change, 2018).

Canada alone has lost 65% of our Atlantic coastal marshes, 80–98% of wetlands within or adjacent to Canada's urban centres, 68% of wetlands that were once present in southern Ontario, over half of the central prairie potholes, and 70% of our Pacific estuary marshes (Canadian Wildlife Service, 1991). It is obvious that there is a lot of room for improvement and many areas where we could increase our number of wetlands.

Cost

The cost of wetland restoration can vary widely. The *Interim Guidelines for Wetland Protection and Conservation in British Columbia* estimate most wetland restoration projects cost between USD 1,000/ha and USD 124,000/ha (Wetland Stewardship Partnership, 2009). One specific project proposed in the Kootenay area of B.C. has an average cost of USD 55,369.44/ha (Biebighauser & Annschild, 2016). In return, such a wetland could prevent USD 5,700/ha per year in flood damages (Ming et al., 2007). Within 10 years, the wetland would pay for itself, and within 20 years, the wetland would mitigate an extra USD 58,630/ha in flood damages (see **Table 1**).

Table 1: Payoff of Restored Wetland Under Different Social Discount Rates (USD/ha)

Year	**0%**	**1%**	**3%**	**6%**
1	5,700	5,644	5,534	5,377
10	57,000	51,600	42,413	31,828
20	114,000	93,428	63,119	35,546

Note. Calculations made using data from Ming et al. (2007).

Flood Mitigation

With the continuous rise of global temperatures, the flood mitigation services of wetlands will become more important than ever. Under the Representative Concentration Pathway 8.5, extreme precipitation events are expected to increase in frequency by two to five times by the end of the century (Alfieri et al., 2017; Swain et al., 2020). In Middlebury, Vermont, Otter Creek floodplains and wetlands were estimated to have prevented 84–95% of damages from Tropical Storm Irene, which equates to upwards of $2,000,000 (Watson et al., 2016). If such a storm happened historically once in 100 years, in the future, one like it may occur once every 50 or even once in 20 years. If these types of storms happen once in 50 to once in 20 years, within 100 years, the Otter Creek floodplains and wetlands would save the residents $4,000,000 to $10,000,000 in damages, on top of the yearly normal flood mitigation.

Conclusion

The ability of wetlands to mitigate flood damage from both common and extreme precipitation events is valuable. Our changing climate will only increase our need for the services wetlands can provide. Restoring a wetland is an investment for a community and can be an important tool for adapting to climate change.

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TECHNOLOGICAL & ECONOMIC ASSESSMENTS

Combustion Engine vs Electric Vehicle: An Economic Assessment

TRAYTON BROWN AND ALEC FLOEN

Introduction

The world has been steadily switching to more fuel-efficient vehicles that produce less emissions. Despite this, we have been very slow to make the change to zero-emission vehicles, such as battery-electric vehicles (BEVs). There are pros and cons to both BEVs and internal combustion engine vehicles (ICEVs). One should consider both the personal and external costs of different vehicle types.

BEV vs. ICEV: Personal Costs

LADIES, BE PATRIOTIC—drive your own
DETROIT ELECTRIC
and avoid the use of gasoline, oil and chauffers, now
needed by the government
ELECTRIC VEHICLE COMPANY
1512 Eleventh Avenue
Phone East 6

***Figure 1**: Detroit Electric Automobiles (1917) (ADVERT 115) (Anderson Electric Car Company/ Wikimedia Commons) Public Domain*

Purchase Price

One of the largest personal costs of purchasing a BEV is the higher purchase price (Hagman et al., 2016; Palmer et al., 2018). Many countries offer subsidies for purchasing a BEV, which may help offset the larger purchase price, although the subsidy might be the reason for the higher purchase price (Hagman et al., 2016; Palmer et al., 2018; Carnex Canada, 2022). Despite subsidies, many people cannot afford to purchase a new BEV, and the market for used BEVs is currently very small. Depreciation rates have not proven to be much different for BEVs compared to ICEVs over three years, according to Hagman et al. (2016). However, other sources suggest EVs depreciate at a faster rate because of government subsidies (Carnex Canada, 2022), indicating that this will vary by country.

Maintenance

The largest advantage of a BEV is the much lower personal costs for maintenance and fuel (Hagman et al., 2016; Palmer et al., 2018). Electric vehicles (EVs) demonstrate lower maintenance requirements due to their mechanical components, fewer moving parts that experience wear, as well as regenerative braking capabilities, which reduce wear on brake parts (Hagman et al., 2016).

Mitropoulos et al. (2017) analyzed passenger vehicle maintenance costs, finding that internal combustion engine vehicles (ICEVs) incur an estimated maintenance cost of $0.0539 per mile. A study assumes that EV maintenance costs are approximately 30% less than those of ICEVs, resulting in an estimated cost of $0.0377 per mile for EV maintenance (Mitropoulos et al., 2017). This estimated cost suggests a significant personal cost advantage for EV owners compared to ICEV owners in terms of ongoing vehicle maintenance expenses. **Table 1** summarises the total costs of ICEV, HEV, and EV vehicles.

Table 1: Personal Costs of ICEV, HEV, & EV in 2023 CAD

Cost Type	**ICEV**	**HEV**	**EV**
Retail	47,074	47,963	54,813
Fuel	19,128	8,768	5,842

Operation	42,506	37,861	41,366
Total Cost of Ownership	108,708	94,591	102,021

Note. Based on 10.6 years and 18,186 km annually (Mitropoulos et al., 2017) Data obtained from 2023, using the U.S. CPI to convert to 2023 from 2015 Consumer Price Index/ U.S. Historical CPI (U.S. Bureau of Labor Statistics, 2024) and the exchange rate to convert to Canadian dollars from the Bank of Canada (n.d.).

BEV vs. ICEV: External Costs

A study was also performed on the total externality costs of gas, hybrid, and electric battery vehicles, comparing all the prices of total externalities costs (Mitropoulos et al., 2017). The highest external costs were gas, followed by hybrid and electric vehicles, with the lowest externality costs of the three groups (Mitropoulos et al., 2017). However, note that this data is from the U.S., which has different methods of producing electricity. Electricity is also much cheaper than fossil fuels and taxed at a lower rate, meaning much cheaper fuel costs for a BEV (Palmer et al., 2018).

For external costs, one should consider things such as air pollution, climate change, noise, and congestion. External costs will vary greatly based on electricity generation methods. For example, a study done in Germany showed that there is no external cost advantage to EVs (Jochem et al., 2016). This finding is likely due to the methods of electricity production in Germany, resulting in greenhouse gas emissions when charging an electric vehicle. BEVs do not contribute directly to urban air pollution, which is a big positive for public health in urban areas (Palmer et al., 2018). Reduced emissions reduce potential climate change impact (König et al., 2021). EVs are often much quieter than ICEVs, which has a positive impact on urban noise pollution (König et al., 2021). Congestion at charging stations may be another reason for their low popularity (Palmer et al., 2018).

Table 2 summarises the total costs of ICEV, HEV, and EV vehicles.

Table 2: External Costs of ICEV, HEV, & EV in 2023 CAD

Cost Type	**ICEV**	**HEV**	**EV**
Greenhouse Gases (GHG)	3,295	1,740	2,073
Air Quality	4,544	4,409	3,267
Time	2,571	1,999	1,560
Total Externalities	10,411	8,148	6,901

Note. Based on 10.6 years and 18,186 km annually (Mitropoulos et al., 2017) Data obtained from 2023, using the U.S. CPI to convert to 2023 from 2015 Consumer Price Index/ U.S. Historical CPI (U.S. Bureau of Labor Statistics, 2024) and the exchange rate to convert to Canadian dollars from the Bank of Canada (n.d.).

BEV vs. ICEV: Total Costs

Table 3 summarises the total costs of ICEV, HEV, and EV vehicles.

Table 3: Total Costs of ICEV, HEV, & EV in 2023 CAD

Vehicle Type	**Total Costs**
ICEV	119,119
HEV	102,739
EV	108,921

Note. Based on 10.6 years and 18,186 km annually (Mitropoulos et al., 2017) Data obtained from 2023, using the U.S. CPI to convert to 2023 from 2015 Consumer Price Index/ U.S. Historical CPI (U.S. Bureau of Labor Statistics, 2024) and the exchange rate to convert to Canadian dollars from the Bank of Canada (n.d.).

Conclusion

A vehicle purchase comes down to an individual's needs and budget, and some scenarios and countries favour both types of vehicles. For an individual who does not do a lot of driving every year, an ICEV would likely be more cost-effective because the lower purchase price would offset higher fuel and maintenance costs. For an individual who does a lot of driving, a BEV would likely be more cost-effective because the amount of money saved in maintenance and fuel would offset the higher purchase price. EVs are effective at reducing greenhouse gas emissions if they are charged with renewable energy sources. However, with advancing technology, BEVs will likely become a lot more cost-effective for the average driver in the future.

Media Attribution

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Cold Climate Conditions & Electric Vehicle Battery Degradation

TERYN CAMERON

Introduction

Growing environmental awareness and a focus on decarbonization have led us toward accelerated electrification. Since the 2015 Paris Agreement, this momentum has only intensified, hoping to lead us to a future of widespread adoption of electric vehicles (EVs). EVs will help us attain our carbon reduction objectives as societies transition away from petrol and diesel and governments worldwide set ambitious environmental targets. For instance, the United States aims for 50% of vehicles sold in 2030 to be electric (Senol et al., 2023; Agarwal et al., 2014).

While setting goals is crucial for progress, it is equally important to ensure they are realistic and accompanied by actionable plans for achievement. The advancement of technologies, such as fracking, has increased our fossil fuel reserves, as seen in countries like the United States, where they are now in the lead in oil and gas production. This change highlights the ongoing tension between technological advancements and our society’s energy consumption habits (Covert et al., 2016).

Challenges of Electric Vehicles (EVs)

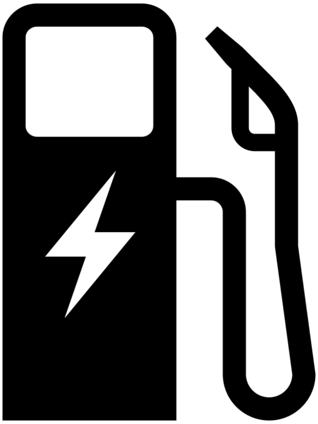

Figure 1: *E-charging station (Tommaso.sansone91/ Wikimedia Commons). CC0 1.0 Universal Public Domain*

Climate

Many countries and regions, such as Canada, Norway, China, and the northern U.S., adopting EVs endure severe winter conditions that are often sub-zero. The lack of adequate industry and literature research in these climates makes it challenging to understand battery degradation, as cold environments tamper with battery lifetime prediction. Due to these knowledge gaps, EV adoption faces difficulties. Additionally, power quality concerns may be introduced if chargers operate below their rated capacity, depending on if higher EV demand is anticipated in winter months. For EVs to compete with ICEs, they need to work efficiently regardless of weather conditions (Senol et al., 2023).

Batteries

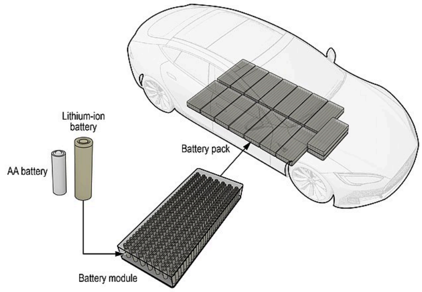

Figure 2: *Electric battery in a car (National Transportation Safety Board/Wikimedia Commons). Public Domain*

Lithium-ion batteries (LIBs) are the most common kind of EV battery today, and they are estimated to be worth approximately $70 billion by 2026, including all modes of transport they are used in (Murugan et al., 2022).

Battery degradation refers to the factors contributing to a decline in battery performance and capacity, including driving habits, charging patterns, environmental conditions, and elapsed time. As temperature decreases, battery degradation increases. For example, at -25°C, the Mitsubishi i-MiEV's driving range decreases to 42 km compared to 128 km at 21°C (Senol et al., 2023). To keep LIBs at a standard lifecycle and health status and avoid the two key dilemmas related to operations (performance loss and degradation), they require heating internally and/or externally. Reliable battery thermal management systems (BTMS) are essential for this purpose.

Conclusion

In conclusion, the shift toward EVs is driven not only by environmental concerns and decarbonization efforts but also by compelling economic factors. The projected market value of LIB cells shows the significant economic opportunities in the EV industry. Furthermore, government initiatives and targets for EV adoption, such as aiming for half of vehicles sold in 2030 to be electric in the United States, highlight the growing importance of EVs in national economies. However, it is important to note that challenges remain, particularly in regions with severe winter conditions, where more research should be done to understand battery degradation and the optimal operation of EVs. Overcoming these challenges will require continued investment in reliable BTMS and innovative solutions to ensure the competitiveness of EVs against ICE vehicles. As we navigate this transition in our society, it is important to find a balance between environmental sustainability and economic viability. This balance will help ensure the benefits of EV adoption extend beyond reducing carbon emissions to driving economic growth and prosperity.

Media Attributions

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Figure 2: "E-charging station (ECS) – electric vehicle (EV) recharging point – supply equipment (EVSE) – colonnina di ricarica elettrica icon" by Tommaso.sansone91 (2019), via Wikimedia Commons, is used under a CC0 1.0 Universal Public Domain license.

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Investigating Economic Consequences of Climate Change on Marine Ecosystems

OLIVIA DAVEY

Introduction

In this short commentary, I aim to observe how the degradation of marine environments from anthropogenic climate change will impact the economy.

Marine ecosystems worldwide are grappling with the profound impacts of anthropogenic climate change, leading to significant alterations in their structure and functioning. These effects are exacerbated by human activities, both directly and indirectly. Direct impacts stem from activities like commercial fishing, offshore drilling, shipping, wind farms, recreational uses, and aquaculture; meanwhile, indirect impacts arise from greenhouse gas emissions and land-use changes (Priya et al., 2023). Additionally, marine ecosystems face numerous unwarranted effects due to the human footprint, including frequent oil spills, pollution, harmful algal blooms, and the introduction of invasive species (Häder et al., 2020). These stressors collectively undermine the resiliency and resistance of marine ecosystems. Consequently, rising ocean temperatures, elevated water levels, and increased ocean acidification pose existential threats, potentially leading to the degradation of vital marine habitats and jeopardizing the sustainability of global fisheries (Priya et al., 2023).

Valuation of Marine Ecosystem Services

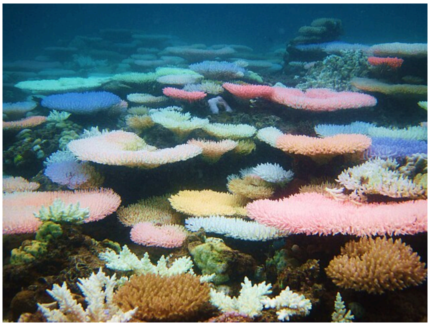

***Figure 1**: Corals glow in neon shades during a 2010 bleaching episode at Palawan, Philippines (Ryan Goehrung/The Conversation). Used with permission.*

The ocean and coastal regions within 100 km of shore contribute a staggering 61% to the world's GDP and supply 15% of the annual protein consumption for 4.2 billion people (Nunes & Gharmandi, 2013). This economic powerhouse sustains densely populated coastal communities, driving poverty reduction, economic growth, food security, and biodiversity preservation while also buffering against the impacts of climate change (Nunes & Gharmandi, 2013).

Despite their invaluable contributions, the true value of marine ecosystems extends beyond monetary metrics, encompassing vital services essential for human well-being.

While the economic benefits of industries like fishing and tourism are easily quantified, the ecological services provided by marine environments, such as carbon sequestration, are often undervalued and difficult to measure (Remoundou et al., 2009).

Coral reefs exemplify this dichotomy, serving as lucrative tourism hubs while facing catastrophic losses due to ocean acidification-induced bleaching (Cornwall, 2021). The decline of coral reefs not only jeopardizes tourism revenue but also disrupts the delicate balance of marine ecosystems, impacting fisheries and biodiversity. These threats are a result of externalities, and their costs will likely be inflicted on those who depend on reefs in some way or another (Cornwall, 2021). When nature contributes to human well-being, it becomes a significant driver of the real economy (Costanza et al., 2014).

Recognizing ecosystem services as common goods underscores the importance of assigning them appropriate value for effective management. Costanza et al. (2014) outline the monetary valuation of marine and ocean biomes annually from 1997 to 2011, as shown in **Table 1**.

Table 1: Valuation of Biomes Between 1997 & 2011

Skip Table 1

Biome	**Area in 1997 (ha)**	**Area in 2011 (ha)**	**Change From 1997–2011**	**Value in 1997 (2007$/ha/yr)**	**Value in 2011 (2007$/ha/yr)**	**Change From 1997–2011**

Marine	36,302	36,302	0	796	1,386	572
Open Ocean	33,200	33,200	0	348	660	312
Coastal	3,102	3,102	0	5,592	8,944	3,352
Estuaries	180	180	0	31,509	28,916	-2,593
Seagrass/ Algae Beds	200	234	34	26,226	28,916	2,690
Coral Reefs	62	28	-34	8,384	352,249	343,865
Shelf	2,660	2,660	0	2,222	2,222	0

Note. Data from Costanza et al. (2014).

Among these ecosystems, coral reefs exhibited the most significant decrease in area and concurrent increase in value. This trend highlights the multitude of ecosystem services they offer, as detailed in **Table 2**. The diminishing coral reef area annually poses a substantial threat to the economy, as evidenced by the marine systems experiencing a loss of 10.9 trillion dollars per year (Costanza et al., 2014). Additionally, the proliferation of dead zones — a direct result of nutrient runoff and fossil fuel emissions — poses a severe threat to fisheries, further exacerbating economic challenges in regions reliant on marine resources (Diaz & Rosenburg, 2008).

Table 2: Valuation of Coral Reef Ecosystem Services Between 1997 & 2011 (2007$/ha/yr)

Coral Reef Ecosystem Services	**1997**	**2011**
Climate Regulation	—	1,188
Disturbance Regulation	3,795	16,991
Biological Control	7	7

Habitat/Refugia	10	16,210
Food Production	3,04	677
Raw Materials	37	22,000
Genetic Resources	—	33,048
Recreation	4,150	96,302
Total Value	8,384	352,257
Total Increase	—	343,873

Note. Data from Costanza et al. (2014).

Conclusion

Addressing these challenges requires a concerted effort to manage marine ecosystems sustainably. While transitioning to eco-friendly practices may incur short-term economic costs, the long-term benefits of preserving marine resources far outweigh the alternatives. However, effective management of marine ecosystems is hindered by jurisdictional complexities and international cooperation challenges (Nunes & Ghermandi, 2013). Yet investing in marine reserves and assigning economic value to ecosystem services offers a promising path forward, ensuring the resilience and prosperity of marine ecosystems for generations to come.

Media Attribution

Figure 1: “Corals glow in neon shades during a 2010 bleaching episode at Palawan, Philippines” by Ryan Goehrung, via The

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The Potential of Hydrogen Fuel Cell Vehicles

ZACHARY JOHNSON

Introduction

The era of hydrogen fuel cell vehicles (HFCV) is approaching soon as technological breakthroughs are occurring rapidly. Provided that HFCV produces zero emission, this short commentary aims to determine the emission and cost of producing hydrogen fuel cells (HFC). Additionally, due to hydrogen likely becoming a major fuel source, this commentary will address the costs and implications regarding the development of hydrogen fueling stations (HFS).

Hydrogen Fuel Cell Vehicles Production

Emissions

Currently, the supply chain of HFCs is driven by a variety of production methods. These methods include the use of fossil fuels such as natural gas reforming, coal gasification, the use of renewable sources of energy for electrolysis such as wind, solar, and hydroelectric, and nuclear reactors, including nuclear fission (Granovskii, 2006; Kothari et al., 2008). Globally, hydrogen (H_2) production is dominated by using fossil fuel feedback systems (Kothari et al., 2008). The proportion of hydrogen produced directly using fossil fuels is 96%, while 4% is produced indirectly using electricity sourced from fossil fuels.

Studies have determined that hydrogen production through electrolysis using wind energy was a greater option for mitigating greenhouse gas emissions, while natural gas reforming showed greater pollution reduction (Granovskii, 2006). Moreover, producing H_2 directly through fossil fuels produces between 7.33 and 29.33 kg of CO_2 per kg of H_2 when at 75% system efficiency. In contrast, H_2 produced by electrolysis with the use of renewable energy sources had zero CO_2 emissions (Kothari et al., 2008).

Figure 1: *Hydrogen program systems integration (Office of Energy Efficiency and Renewable Energy/Energy.gov). Public Domain*

Moreover, if, on average, HFCV efficiency is 1 kg H_2/100 km and the average person in Canada drives 20,000 km per year, then 200 kg of H_2 is used per year, which equates to 1,466 to 5,866 kg of CO_2 emitted H_2 production using fossil fuels (Winkless, 2016).

For electric vehicles (EV), the average CO_2 emitted from battery production is 100 kg equivalent per kilowatt hour (kWH) (Linder et al., 2023). The U.S. Department of Energy (2020) estimates that, when considering production and the lifetime of an EV, the annual CO_2 emissions are equivalent to 1,237 kg per vehicle annually. When comparing internal combustion engines (ICE), the fuel economy for a gasoline engine is 8.9 L/100 km and for every litre of gasoline burned, 2.3 kg of CO_2 is emitted. Lastly, in a year of driving 20,000 km, this is equivalent to 4,094 kg of CO_2 annually per vehicle. A summary of the annual emissions is shown in **Table 1**.

Costs

The cost of producing H_2 shows great variation, depending on the processing method. The cost for natural gas reforming (NGR) is 103.6 RS/kg, where RS is capital cost (USD 1 = 44 RS), which is equivalent to USD 2.4 / kg H_2 (Kothari et al. 2008). Electrolysis varied depending on the energy source, and it was determined to be between 73.5 RS/kg (USD 1.67 / kg H_2) and 854.3 RS/kg (USD 19.4/kgH_2).

The annual cost of an HFCV would then be equal to CAD 480 per year to operate, assuming 200 kg of H2 is used per year and the method of production is NGR. In comparison, an EV uses approximately 15 kWH per 100 km, and a year's worth of driving (20,000 km) is equal to 3,000 kWH. The cost of charging at Tesla stations is CAD 0.26 per kWH, and if 3,000 kWH are used annually, then it would cost $780 to operate (Energuide.be, n.d.). The average cost of regular gasoline is CAD 1.68/L, and in a year, an ICE would burn 1,780 L of gasoline, costing the operator CAD 2,990 annually. A summary of the annual operating cost of vehicles is displayed in **Table 1**.

Table 1: Comparing Annual Emissions & Costs Between Vehicle Types

Vehicle Type	**Annual Emissions (kh CO_2)**	**Annual Operator Cost (CAD)**
Hydrogen Fuel Cell	1,466 to 5,866	480
Electric	1,237	780
Internal Combustion Engine	4,094	2,990

Note. Annual emissions from the U.S. Department of Energy (2020). Annual operator costs from Kothari et al. (2008) and Energuide.be (n.d.).

Hydrogen Fuel Station Production

As of 2013, there were 224 HFS globally, with 43% in the Americas, 34% in Europe, and 23% in Asia (Alazemi and Andrews 2015). HFS is designed to either have H_2 delivered to the station, produce H_2 on-site, or even a combination of the two. HFS construction costs between USD 1.8 and 5.9 million in the U.S. (Richardson et al. 2015). Typically, the stations have fixed capacities of H_2/day, such as 60 to 1,000 kg/day (Richardson et al., 2015; Aminudin et al., 2023). The average cost of an HFS is USD 2.4 million for 500 kg/day or USD 5.7 million for 1,000 kg/day; however, the cost will vary depending on the method of H_2 production (Aminudin et al., 2023). HFS require expensive safety devices, which add to the cost, as hydrogen is very combustible, with a range of 7% to 45% in the air (Richardson et al., 2015). HFS's high cost and lack of flexibility deter private investors, resulting in the financial burden belonging to governments.

Conclusion

In conclusion, as we move into the HFCV era, we can expect that HFC production and HFS will be extremely expensive. However, with enough traction and technological advancements, the costs may drop. It is recommended that HFCs be developed using electrolysis using hydrogen power as it's the most cost-effective and environmentally efficient production method. Additionally, hydrogen fuel cell vehicles appear to be the best option compared to electric and ICE as they offer similar emissions to EVs and the lowest operating cost.

Lastly, due to the financial burden of developing HFSs falling on governments, it is recommended that they have incentives for the public to switch to HFCV. However, the implementation of a tax would not work as the tax rate would be extremely high to equal the marginal environmental damages (Sartzetakis & Tsagaris, 2005). Subsidization was also determined to be an insufficient option as the tax rate would be too low and not equal the marginal environmental damages. A possible incentive could be replacing old internal combustion technology with the new HFC technology. The government could subsidize the cost of switching technologies to account for vehicle depreciation. Lastly, we could convert gas stations into HFS to encourage the switch to HFCVs, although this was proven to have a low chance of success.

Media Attribution

Figure 1: “Hydrogen Program Systems Integration” by the Office of Energy Efficiency and Renewable Energy [an office of the U.S. Department of Energy] (n.d.), via Energy.gov, is in the public domain.

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Satellite Technology, Methane, & Climate Change Economics

PATRICK IZETT

Introduction

Unlike CO_2, atmospheric methane (CH_4) concentrations have risen faster than ever in the past two decades and, since 2014, are now approaching the most greenhouse-gas-intensive scenarios (Saunois et al., 2016). CH_4 is responsible for roughly 30% of the rise in global temperatures since the Industrial Revolution, so the need for immediate reductions in CH_4 emissions is imperative to limiting global warming and improving air quality (International Energy Agency [IEA], 2023). However, with advancements in satellite imaging, the ability to map global CH_4 leaks in real-time has become increasingly more accessible. The UN Environment Programme estimated that the global cost of adapting to climate impacts is expected to grow to $140-300 billion per year by 2030 and $280-500 billion per year by 2050, with the estimated costs of damages from warming in 2100 for 1.5 C and 2 C were $54 trillion and $69 trillion (Black, 2014).

Using Satellite Technology to Combat Climate Change

Satellite technology is at the forefront of the advancements made in combating climate change, with these satellites able to capture information in real-time. We can distinguish three major parameters that help us characterize satellite observations: spectral resolution, spatial resolution, and temporal resolution (Olczak et al., 2020). Furthermore, these satellites provide “hyper-spectral images in a short-wave infrared (SWIR) spectrum, in which CH_4 is a strong absorber (Ehret et al., 2022). Traditional methods for mapping CH_4 struggle to identify key areas around the globe. Surface stations located in South America, Central Africa, Southeast Asia, and Boreal Eurasia, all of which are key regions for CH_4 emissions, where these traditional methods are unable to accurately identify CH_4 leaks (Pison et al., 2013). Currently, satellite technology detects CH_4 plumes using Tropospheric Monitoring Instrument sensors that can identify source locations by longitude and latitude (Kayrros, n.d.).

Reducing Methane Leaks

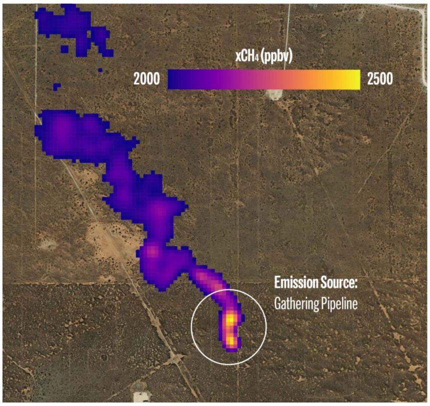

Figure 1: *MethaneSAT's algorithm and sensing technology can also detect the rate of methane emissions escaping from specific oil/gas sources.* (MethaneSAT/ *Environmental Defense Fund) Environmental Defense Fund Terms of Use*

According to economic theory, companies will capture methane emissions if the economic costs of doing so are less than the value of the lost gas (Hausman & Raimi, 2019). While there are some economic incentives to prevent methane leaks, there are not enough. From an outside perspective, the damage caused by each additional MMBtu of methane emissions ranges from \$2.80 to \$27 of value lost from gas in the U.S. (Hausman & Raimi, 2019). In addition to the direct costs, the indirect costs of methane leaks affect agricultural productivity through ozone and climate change. Recent studies have found evidence of consequences to health and agricultural damage to be larger than previously believed. Most identified methane abatement controls cost less than the societal benefits of USD 4,300 per tonne of methane. Reducing these CH_4 emissions would equate to a global saving of roughly USD 470 billion (Climate and Clean Air Coalition [CCAC] & United Nations Environment Programme [UNEP], 2021).

Advantages

The key advantage of utilizing satellite technology to detect CH_4 plumes is the ability to observe the vast diversity of CH_4-emitting sectors. Plumes from different sectors have different shapes and sizes (Ayasse et al., 2019). For example, satellites can infer different trends in CH_4 mapping, providing data on source types such as oil and gas, livestock, and wetlands. Case studies by Cusworth et al. (2018) and Pandey et al. (2019) further illustrate the use of satellite tech and its economic viability. Each study uses TROPOMI observations to discover different plumes of CH4 in the U.S. (Nisbet et al., 2020). Highlighting these leaks allows for real-time action and the ability to map where attention is needed. With economic incentives to innovate and continually abate methane, satellite technology and data collection are at the forefront of addressing methane emissions (Olczak et al., 2020).

Furthermore, satellite technology can aid in the performance and analysis of the marginal abatement cost (MAC). The MAC shows the added costs of achieving a 1-unit decrease in the emission level. **Table 1** shows eight sources of potential abatement and marginal abatement costs for the Canadian national aggregate methane. The first 7.5 million tonnes can be reduced at a marginal benefit using gas capture technology, electric pump and instrument air. Reductions after 7.5 million tonnes of marginal abatement costs are positive. Furthermore, old technologies have a higher MAC for any given reduction of emission than newer, cleaner technologies. Therefore, employing new satellite technology will aid in MAC and the lowering of methane emissions around the globe.

Table 1: Potential Abatement & Marginal Costs for Canadian National Aggregate Methane

Source	**MAC (\$/tonne CO^2e)**	**kTonnes CO^2e Reduced**
Compressor Blowdowns – Gas Capture	-12	2,500
Kimray Pumps – Electric Pump	-11	5,000
High Bleed Pneumatic Devices – Instrument Air	-10	7,500
Liquids Unloading – Controlled	1	5,000
Centrifugal Compressors (Blowdown Valve) – LDAR	2	12,500
Reciprocating Compressor Rod Packing – LDAR	3	17,500
Pipeline Venting – Pump Down	8	20,000
LDC Meters and Regulators – LDAR	41	25,000

Note. Marginal abatement cost table for methane reductions by eight sources. Approximate values from ICF International for the Environmental Defense Fund (ICF International, 2015). EDF Terms of Use

Conclusion

In summary, the need for immediate reductions in CH_4 emissions is imperative to limiting global warming and improvement of air quality (IEA, 2023). With the advancements in technology and satellite imaging, the ability to map global CH_4 leakages has become more accessible. While there are some economic incentives to prevent methane leaks, there are not enough. Governments need to act now with a genuine effort to effect change. To have the possibility of global savings of roughly USD 470 billion if emissions are reduced (CACC & UNEP, 2021). As technology continues to advance, the use of satellites will be crucial in affecting the MAC and global CH_4 emissions.

Media Attributions

Figure 1: "MethaneSAT's algorithm and sensing technology can also detect the rate of methane emissions escaping from specific oil/gas sources" by MethaneSAT (n.d.), via Environmental Defense Fund, is used under the Environmental Defense Fund Terms of Use.

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The Economic Feasibility of Geoengineering Solutions

CLINTON KABONI AND LAUREN VIESNER

Introduction

This commentary offers a comprehensive examination of the economic dimensions of geoengineering, focusing specifically on the contrasting strategies of carbon dioxide removal (CDR) and solar radiation management (SRM) discussed by Harding and Moreno-Cruz (2019) and the economics of geoengineering. Their analysis goes into each approach's distinct methods and impacts and highlights the cost-effectiveness and timescales associated with their implementation.

Carbon Dioxide Removal vs. Solar Radiation Management

Within the context of geoengineering, CDR involves removing and storing CO_2 in the atmosphere, while SRM attempts to reduce global temperatures by reflecting solar radiation (Harding & Moreno-Cruz, 2019). Because of their innate differences, they both involve differing methods of controlling climate; thus, their cost and timescales also vary. Harding and Moreno-Cruz discussed that between the two strategies, SRM exhibits lower cost and its impact on climate change is observed within months rather than decades. In contrast, SRM is seen as the opposite, demonstrating high cost and being much slower to impact. However, SRM is limited, cannot address all climate change, and may even introduce more problems in the future. As for CDR strategies, while they are much slower and expensive, they perfectly counteract climate change. However, the cost and speed of this strategy are comparable to traditional mitigation.

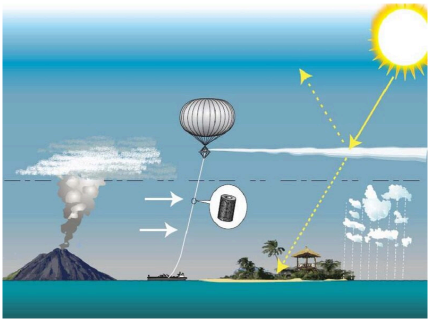

***Figure 1**: Solar radiation management (Hughhunt / Wikimedia Commons)* CC BY-SA 3.0

For SRM, the cheapest technique is stratospheric aerosol albedo modification, which reduces the radiative forcing of sulphate particles released into the stratosphere. This could be done using current technology, such as releasing these particles using naval rifles, airplanes, balloons, or constructing large towers (Harding & Moreno-Cruz, 2019). Robock et al. (2019) state that the cost for these different methods of injecting 1 Tg of sulphur gas per year into the stratosphere ranges from 1.2 to 30 billion dollars a year. This cost range depends on the technology used and the preferred particle levels. (Harding & Moreno-Cruz, 2019).

With CDR, many techniques may be utilized, with direct air capture (DAC) being mentioned the most in the literature, which is when CO_2 is directly taken from the air and then stored. The cost of this technique varies considerably; Harding and Moreno-Cruz (2019) write that initial estimates for direct air capture at an industrial level find implementation costs of around USD 30 to 100/tCO_2. Follow-up research incorporating the innovation of technologies, learning, and commercial expansion finds higher costs ranging from USD 200/tCO_2 to as high as USD 1,000/tCO_2 initially, but also finds they can fall to between USD 30/tCO_2 and USD 300/tCO_2 later in the century. According to Harding and Moreno-Cruz, many researchers have concluded that direct air capture expansion may be feasible; however, once their high costs decrease from further advancements, it will continue to have a limited impact on climate change.

This commentary acknowledges Scheider's (2008) concerns about geoengineering feasibility, especially regarding international cooperation and governance challenges. Scheider highlights potential conflicts due to differing ideologies, emphasizing the need for transparent and fair governance. These challenges and economic considerations raised by Harding and Moreno-Cruz (2019) underscore the complexities of geoengineering strategies.

Table 1 summarises how CDR compares to SRM.

Table 1: Comparing Carbon & Solar Geoengineering

Methods	**Description**	**Cost**	**Benefits**	**Risks/Costs**
Carbon Dioxide Removal (CDR)	Seeks to directly remove carbon dioxide, generated from economic activity using fossil fuels and land use changes, from the atmosphere. Globally, we emit 40 gigatonnes a year.	Costs can be high, particularly for large scale implementation. $30 up to $1,000 per tonne of CO_2.	• Helps reduce greenhouse gases and mitigate climate change but does not directly address the warming effect of greenhouse gases already in the atmosphere.	• Still in experimental/ developmental stages. • Require a lot of energy, land, and water resources. • Some CDR methods, such as fertilization, may have uncertain reversibility if it is found to be harmful or ineffective. • Concerns about the distribution of costs and benefits among different regions and communities. • Most expensive method. • Involves manipulation of natural systems and could divert attention from the need to reduce emissions.
Solar Radiation Management (SRM)	Seeks to reflect a small fraction of sunlight into space or increase the amount of solar radiation that escapes back into space to cool the planet.	Costs 1.2 to 30 billion dollars a year. It varies depending on the method, but some solar geoengineering techniques may be relatively inexpensive compared to traditional mitigation strategies.	• Offers potential for rapid offsetting of some of the warming effects of greenhouse gases, providing short-term response to mitigate climate	• Could harm regional climates, precipitation patterns, and ecosystems. For example, it may disrupt the Asian and African monsoons, impacting the agriculture and water

			change impacts. - It is inexpensive to implement. - It can be used as a last resort offering a broad-scale approach to climate mitigation.	resources. - Need international cooperation, consensus, and oversight to ensure equitable distribution of risks and benefits. - It may not perform as expected or could have unforeseen effects. - Poorly deployed solar geoengineering technologies could exacerbate geopolitical tensions, leading to conflicts over control, governance, and unintended impacts.

Note. Data from Burrow (2018), Corry (2017), Faran & Olsson (2018), Gunderson et al. (2018), Harding & Moreno-Cruz (2019), Harding et al. (2020), Robock et al. (2019), Scheider (2008), and Tollefson (2018).

Conclusion

While geoengineering may seem like a tempting solution to mitigate the effects of climate change, it is fraught with uncertainties and risks, especially given the current difficulty in coordinating a response to climate change. CDR and SRM offer climate risk mitigation alternatives. More research on the impacts and damages from climate engineering is needed to inform policy decisions and ensure responsible implementation, considering its environmental, climatic, and societal implications. Ultimately, investing in mitigation measures and exploring alternative methods to reduce our impact on the Earth should remain paramount as we navigate the challenges of climate change.

Media Attribution

Figure 1: "SPICE SRM overview" by Hughhunt (2011), via Wikimedia Commons, is used under a CC BY-SA 3.0 license.

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Unravelling Threads of Change: Economic & Climate-Induced Migration in the Sahel

NALEDI MOLAI AND ASHLEY THOMSON

Introduction

The Sahel region in Africa encompasses parts of Senegal, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, and Sudan. It has a unique climate with variable weather patterns and is recognized as one of the more severely affected regions of the world by climate change (Sossou et al., 2019; United Nations Development Programme [UNDP], 2024). This commentary explores the complex interplay between climate factors, economic factors, and migration patterns in the Sahel.

The Sahel Region

***Figure 1**: Coucher de soleil au sahel Cameroun (Minette Lontsie/ Wikimedia Commons). CC BY-SA 4.0*

It is widely agreed that political, economic, social, and environmental factors contribute to the decision to migrate (Teye & Nikoi, 2022; Office of the United Nations High Commissioner for Human Rights [OHCHR], 2021). Migration is a strategy to find alternate sources of income and improve socioeconomic conditions (OHCHR, 2021; Mbiyozo, 2020). In the Sahel region, socioeconomic conditions are strained by the impacts of climate change (Sossou et al., 2019; OHCHR, 2021; Teye & Nikoi, 2022).

Climate Change Effects

There has been a clear decreasing trend of rainfall in the Sahel since the 1960s (Dai et al., 2004; Sissoko et al., 2010). A decrease of 20% to 40% was noted between 1968 and 1990 (Dai et al., 2004). Over the past half-century, the region has endured four major droughts – in 1973, 1984, 1990, and 2012 (Teye & Nikoi, 2022). Additionally, the Sahel has experienced many disastrous floods (UNDP, 2024). These extreme weather patterns negatively impact agricultural yields (Sossou et al., 2019). Predictions from 16 studies indicate a median reduction of 18% in future crop yields across Sudano-Sahelian nations due to climate change, as it reduces the natural capital and fertile land in the Sahel (Roudier et al., 2011; McMichael et al., 2012).

The OHCHR (2021) reports that 79% of Sahelian residents are farmers in rural regions who rely on agriculture for income. Due to reductions in crop yields, many farmers are forced to migrate seasonally or permanently (Teye & Nikoi, 2022). As of December 31, 2023, there are at least 4 million internally displaced people (IDPs) in the Sahel region (UNHCR, 2024b). Furthermore, it is predicted that by 2050, the urban population of these Sahelian countries will be approximately 440 million, and the total population will be over 700 million (United Nations, Department of Economic and Social Affairs, Population Division, 2018). As populations continue to increase, policies must be implemented to assist the increasing amount of IDPs and to allow Sahelian countries to adapt to and prevent climate change.

With volatile macroeconomic situations, a lack of public resources, and ongoing violent conflicts, Sahelian governments cannot provide adequate support to many migrants, leaving them more vulnerable to exploitation. (UNDP, 2024; OHCHR, 2021; Mibiyozo, 2020). Population growth will further strain these governments. **Table 1** summarizes climate, conflict, migration, and urbanization-related challenges facing each of the eight Sahelian countries studied in this commentary.

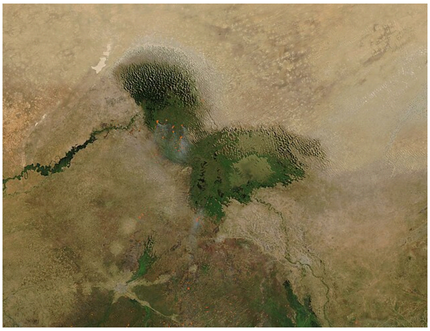

Figure 32: *Fires near Lake Chad (MODIS 2021-10-14) (MODIS Land Rapid Response Team, NASA GSFC/ Wikimedia Commons). Public Domain*

Strategies For Supporting Migration

Considering the information presented in **Table 1** and this commentary, it is critically important that aid organizations and Sahelian governments support migration in the region (Mbiyozo, 2020; Teye & Nikoi, 2022). Infrastructure, economic, and social support are among the most important changes that must be made to allow citizens to live in safe and prosperous conditions (Mbiyozo, 2020; UNDP, 2024).

The UNDP (2024) suggests a long-term investment in clean energy will help transform urbanizing Sahelian economies, as this area has a high potential for solar energy. The International Monetary Fund (IMF, 2023) suggests that international investment and aid are necessary to fund social programs and move towards a sustainable future in the Sahel. The regional nature of the challenges suggests that a collaborative effort between Sahelian Governments will be crucial. Mbiyozo (2020) recommends that solutions be integrated within all levels of government and community organizations.

Table 1: Summary of Challenges, Effects on Urbanization, & Results of Climate Change

Country	Challenges	Effects on Urbanization	Results
Burkina Faso	• Weather extremes impact agriculture, rural livelihoods, and urban food security • Droughts and floods lead to migration (Zickgraf et al. 2016; Teye & Nikoi, 2022)	• Inadequate urban planning, services, and governance issues lead to informal settlements and urban sprawl in major cities (UN-Habitat, n.d.)	• Urban population: 15.5% in 1996 to 31.5% in 2016, projected 52% by 2050 • Growth rate: 4.99% (2015-2020) (UN-Habitat, 2024)
Mali	• Desertification, flash floods, temperature rise affect agriculture yields and increase migration (Teye & Nikoi, 2022)	• Armed conflict, poverty and hunger drive displacement to urban areas and stress capacities (Hummel, 2016; Teye & Nikoi, 2022)	• About 400,000 IDPs as of Dec. 31, 2023 • 55,000 Malians fleeing conflict into Mauritania in 2023 (UNHCR, 2023; UNHCR, 2024b).
Mauritania	• Drought and water scarcity impact livelihoods and hunger • Rising sea levels threaten coastal areas (Zickgraf et al. 2016; Teye & Nikoi, 2022).	• Influx of Malian refugees in Nouakchott and Nouadhibou due to conflict • Lack of basic services • Urgent adaptation and planning needed (UNHCR, 2024b)	• Severe humanitarian and protection crisis • Significant refugee movements • Over 200,000 displaced persons (UNHCR, 2024c; UNHCR, 2024b)
Nigeria	• Rising sea levels, flooding, and changing rainfall patterns affect agriculture and drive urban migration (Teye & Nikoi, 2022; Zickgraf et al. 2016).	• Conflicts over scarce resources leading to internal migration • Rapid unplanned urbanization and lack of infrastructure (OHCHR, 2021; Aliyu & Amadu, 2017).	• Population growth in urban centers • Capital Lagos has a population of about 20 million with 6% annual growth • Over 3 million IDPs as of Dec. 31, 2023 (United Nations Environment Programme, n.d.; UNHCR, 2023)
Sudan	• Desertification, reduced rainfall driving migration as agriculture becomes unsustainable. • Unequal access to clean	• Economic/social service concentrated in Khartoum, causing sprawl and inequality • Migration due to	• Khartoum's population skyrocketed: 250,000 in 1956 to 4.5 million officially in 2005 and over 7 million

	water, particularly in squatter settlements and IDP camps, intensify conflicts over resources (Assal, 2008)	disasters • Strain on urban infrastructure and services (Assal 2008)	unofficially • IDPs in Khartoum lack support from the government (Assal, 2008)
Niger	• Droughts and erratic rainfall affect food security and livelihoods, and drive rural to urban migration (World Bank, 2021b)	• Rapid population growth and integration challenges • Limited decentralization progress (World Bank, 2021a)	• Focus on efficient service delivery amidst rapid urban growth • Development of water harvesting techniques, irrigation systems, and water storage facilities (World Bank, 2021b; World Bank, 2021b).
Senegal	• Coastal erosion and flooding affect Dakar • Impacts on agriculture push rural to urban migration (Rigaud et al., 2021)	• Economic migration without planning leads to urban poverty • Inadequate urban infrastructure and poor service delivery (Rouhana & Ranarifidy, 2016)	• Economic and political factors like neighbors • Refugees, who are citizens of ECOWAS, request provisions for freedom of movement and access to the labor market (UNHCR, 2017)
Chad	• Drought frequency, desertification affect agricultural productivity and livelihoods (UNHCR, 2024a)	• Conflicts and environmental challenges cause displacement and urban strain (Internal Organization for Migration, 2022).	• Internal migration influenced by search for opportunities, impacts of instability • To date, 2,162 individuals (636 households) relocated from the villages of Ademour and Dornong to Kerri (UNHCR, 2024a)

Note. Data from cited sources in the table. The first column summarizes the effects of climate change impacting the eight Sahelian countries studied in this commentary. The second column is an overview of urbanization and migration trends and challenges in each country. The third column is an overview of the impact these climate and migration trends have had on each country's urban population and internal displacement.

Conclusion

Migration to find better economic opportunities in the Sahel will persist as climate change worsens. The number of IDPs will continue to rise due to more frequent disasters and conflicts, combined with population growth. It will require an internationally collaborative solution to aid migrants facing economic and social challenges. Furthermore, there is limited material on the economic impacts of climate change-induced migration in the Sahel. There is an opportunity for more research in this area.

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SPECIFIC NATIONAL/ REGIONAL POLICY ASSESSMENTS

How Feasible Are the 2050 Targets for Costa Rica?

AINSLEY MUTRIE AND MOSES OYELAKIN

Introduction

This commentary explores how feasible the net-zero carbon emission goals of Costa Rica are regarding the target year of 2050. It discusses the goals and implementation of the nation's National Decarbonization Plan (NDP), the biggest challenges for the country to overcome to achieve net-zero emissions, and the main sectors of focus to achieve this. Further, various uncertainties, including reliance on constant parameters to achieve hitting target goals and future costs surrounding investment and technology, surround and may hinder the goals of the NDP.

Costa Rica's National Decarbonization Plan

Involving every sector in the country and stemming from data on the country's major GHG emissions sources, Costa Rica's implemented NDP lays out the process to achieve net-zero emissions by 2050 ("Costa Rica releases national plan," 2019). The plan identifies ten decarbonization categories and acknowledges the need to transform and implement short-to-long-term strategies and more. Some categories include changes to the transportation, agricultural and forestry sectors, changes to industrial processes/associated wastes, and consolidating the electrical grid to support the demand change from non-renewables to renewable/electric energies (Groves et al., 2020). The plan identifies eight strategies and five priorities of action and includes propositions, such as green tax reform, comprehensive reform of institutional, knowledge and digitalization-based economic strategy, the renewal of public transport and agricultural sectors, and creating the appropriate foundations for the electrification of the country ("Costa Rica releases national plan," 2019).

Table 1 summarises Costa Rica's National Decarbonization Plan.

Table 1: Summary of Costa Rica's National Decarbonization Plan

Aspect	**Details**
Target Achievement Year	2050
Net Zero GHG Emissions Goal	Achieved under NDP by 2050
Net Economic Benefit (2020-2050)	$41 billion (discounted at 5% per year back to 2015)
Total Benefits	$78 billion
Total Costs	$37 billion
Major Reduction Sectors	• Transport — 7.4 MtCO2e • Agriculture, livestock, and forestry — 6 MtCO2e • Buildings, industry, and waste — 5.4 MtCO2e

Emissions Without NDP (2050)	Nearly 19 MtCO2e
Current Emissions	Approx. 12 MtCO2e

Note. Data from Groves et al. (2020).

Achieving Decarbonization in Costa Rica

Figure 1: *Tilaran windmill (Richie Diesterheft/Wikimedia Commons).* CC BY 2.0

The Transport Sector

The literature agrees the transport sector is the highest emitter of emissions for Costa Rica, and to reach 2050 goals, dramatic changes need to occur to achieve the desired results. Since the transport sector accounts for 50% of the country's net emissions, it should be decarbonized by 85-95% to achieve the 2050 goals (Quirós-Tortós & Victor-Gallardo, 2023). Noting that decarbonization needs to be partnered with the electrical sector, decarbonization not only equates to electrification but highlights the need to increase infrastructure to support this transition and to support public and non-motorized transport (Quirós-Tortós & Victor-Gallardo, 2023). Quirós-Tortós (2019) points out three key challenges, in particular, that inhibit the overall uptake of EVs in Latin America, including "lack of incentives, insufficient charging infrastructure, and the low-cost effectiveness of EVs." These limitations may inhibit Costa Rica's ability to achieve its NDP goals.

Financial & Non-Financial Incentives

The literature highlights both financial and non-financial incentives to be able to achieve decarbonization goals. Financial incentives include government involvement by implementing reduced taxes and rebates to reduce the upfront costs of EVs to consumers (Quirós-Tortós et al., 2019). Sartzetakis and Tsigari (2005) note that clean technology will not be adopted without regulation because the first users will bear the highest associated costs with the technology and will choose the "dirty" or more cost-effective technology/option by default. They conclude by mentioning that in most cases, a high tax is evitable and that the "Pigouvian tax will not be sufficient" (Sartzetakis & Tsigaris, 2005). Non-financial incentives examples include adding dedicated EV infrastructure such as parking spaces, charging stations and sharing bus lanes. Moreover, EV users are exempt from specific driving restrictions (Quirós-Tortós et al., 2019). Having a significant amount of charging stations is critical to support the current and projected demand for electrical use, and it is an important incentive when considering the increased uptake of EVs and the lack of such implementation would hinder Costa Rica's progress (Groves et al., 2019). Other hindrances observed by Sartzetakis and Tsigaris (2005) note that the benefits derived from a change in clean technology rely on the number of consumers "making the same choice," as this is how the number of users and numbers of stations could theoretically increase.

Uncertainties

Uncertainties are large and varied, as estimates for 30 years from now are littered with assumptions and uncertainties (Groves et al., 2020). Uncertainty includes surrounding costs of future technology, the long-term health of Costa Rica's forests, which are being relied on for carbon sequestration and uncertainty related to the consequences of "failed" target requirements.

Conclusion

The literature agrees that no matter the level of changes that occur, a positive impact will occur and that these changes are in line with the already existing developmental goals of Costa Rica. The literature also agrees that if Costa Rica can facilitate these policies and changes, their targets of net-zero and maintaining a 1.5C are feasible.

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Will Canada Hit Net Zero Emissions by 2050?

CONOR BROWN

Introduction

In this short commentary, we explore the optimistic goals that Canada has set to reach net zero emissions by 2050 (Conigrave, 2023).

How Canada Can Achieve Its Net-Zero Goal

Looking at Canada's Nationally Determined Contribution under the Paris Agreement, Canada has committed to reducing Greenhouse Gas emissions by 40-45% by 2030 compared to levels recorded in 2005 (Dillon, 2016). For Canada to achieve its emissions reduction targets by 2030 and transition to a net-zero economy, it is essential to incorporate forest management adaptations to address climate change alongside mitigation efforts and the use of technologies such as carbon sequestration. Giving preference to industrial processes that produce negative emissions, such as biomass feedstocks, coupled with carbon capture and storage, are crucial steps for a successful transition and will produce significant attention towards policy formulation and fund allocation (Maenz, 2022). To meet the goal of keeping annual global temperature increases below two degrees, Canada must set a 2030 target of reducing GHG emissions by at least 73% below the 2005 levels. Canada would need to make even larger emission reductions to achieved its 1.5°C goal (Dillon, 2016).

Jonathan Wilkinson, Minister of Environment and Climate Change, stated:

> “Our plan to fight climate change and grow the economy is working. Our climate plan is on track to deliver the biggest cut to Canada’s emissions ever, because we’re pricing pollution, investing in clean energy, doubling the amount of nature we protect, and making our air cleaner by phasing out coal power. While we have made a lot of progress over the last four years, we know there’s much more to do. We’re committed to exceeding our 2030 Paris target and getting to net-zero emissions by 2050, as well as to putting our five-year targets into law. To help us get there, we are committed to implementing new measures that will cut pollution faster–such as planting 2 billion trees and other

> nature-based solutions, cutting energy waste and energy bills, making clean power more available, protecting and conserving more of Canada’s lands and oceans than ever before, supporting zero-emissions clean tech companies, and more. We continue to work towards being more ambitious to ensure a cleaner, more prosperous future for our kids and our grandkids.”

(Environment and Climate Change Canada, 2019)

The Canadian Net-Zero Emissions Accountability Act

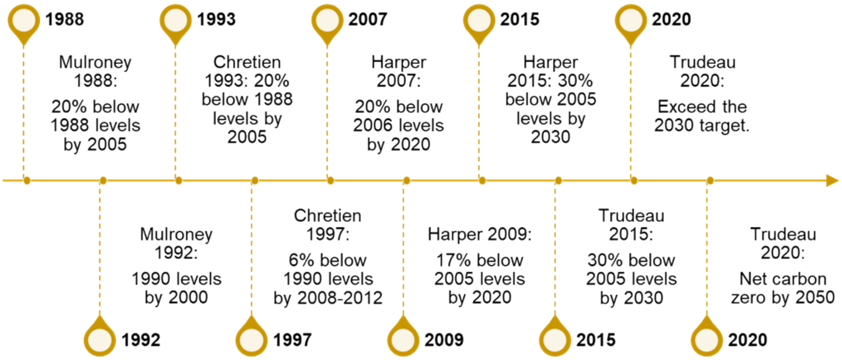

Figure 1: *Federal government pledges since 1988 to date.* CC BY-NC-SA 4.0

Enacted on June 29, 2021, the Canadian Net-Zero Emissions Accountability Act establishes Canada's pledge to achieve net-zero emissions by 2050 within the law (Service Canada). However, the past evidence shows that the Canadian government has never met its targets and obligations (see **Figure 1)**. The current government pledge is a significant investment in the fight against climate change, which previously failed, so meeting our 2030 and 2050 goals is crucial. However, a radical shift towards CO_2 emission mitigation strategies to save energy and replace fossil fuels with clean energy sources is difficult, especially in minimizing negative effects on economic activity and living standards

(Conigrave, 2023). Although the Canadian government has used carbon pricing, regulations, investment incentives, and green technology innovations to transition and balance a sustainable economy, it still needs to do more to meet the ambitious targets for 2030 and 2050. It is important that not only the Federal government acts but provinces and territories must be onboard to help accelerate the green transition.

Conclusion

According to the analysis gathered from the Climate Action Tracker, Canada's climate action and emissions show that the current and planned measures are highly insufficient to meet the targets for limiting global warming (see **Figure 2**) (Climate Action Tracker, 2022b). While land use and forestry have historically balanced as sources and sinks for emissions, Canada's policies fall short of the necessary reductions. Unfortunately, Canada's commitments are not on track to align with either its own modelled pathways or its fair share of global efforts.

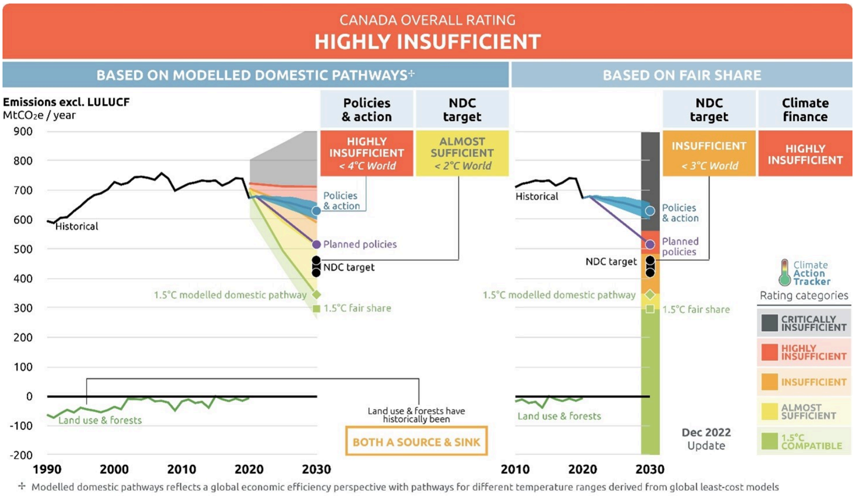

Figure 2: *Canada's overall rating: Highly insufficient (Climate Action Tracker, 2022a) Copyright Policy*

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