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Economics of Climate Change at COP30: Allerts from a Tribute to William Nordhaus

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Summary
Climate economics is now a recognized branch of economic theory that connects basic science with climate mitigation and adaptation policies, translating scientific predictions about physical systems into projections about economic growth and the well-being of societies. This article traces the evolution of this new climate approach from traditional economic worldviews, seeking to consistently address the following question: is there an economics of climate change? How a nascent economics of climate change is forging its path in developing responses to the climate crisis, pioneered by its patron William Dawbney. Nordhaus . Based on the theoretical framework that underpinned the work of William Dalbney Nordhaus , we sought to discuss the salient features of the models developed, as well as the controversies and debates of the last 60 years. In an environment of proliferating hypotheses and scenarios shrouded in uncertainty, Nordhaus can be recognized as a pioneer in the development of integrated economic assessment models (IAM) for climate policies, which underpinned trends and led to epic debates. From the 1970s to the 1990s, GHG taxation was the textbook of environmental economists, influenced by the Pigouvian Solution. Only in the 2000s did carbon markets become widespread as the primary remedy for the climate crisis, becoming dominant, despite the uncertainties surrounding these policies' outcomes. Pricing the negative externalities of climate change, via price signals, also evolved through an evolutionary process.

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path in developing responses to the climate crisis, pioneered by its patron, William Dalbney Nordhaus. Drawing on the theoretical framework that underpinned the work of William Dalbney Nordhaus, this article discusses the salient features of the models developed, as well as the controversies and debates of the last 60 years. In an environment of proliferating hypotheses and scenarios shrouded in uncertainty, Nordhaus can be recognized as a precursor in the development of integrated economic assessment models (IAM) for climate policies, which have underpinned trends and led to significant debates. From the 1970s to the 1990s, GHG taxation was the textbook of environmental economists, influenced by the Pigouvian Solution. Only in the 2000s did carbon markets become widespread as the primary remedy for the climate crisis, becoming dominant, despite the uncertainties surrounding the outcomes of this policy. Pricing the negative externalities of climate change, via price signals, also evolved through an evolutionary process.

Keywords: climate change economics, climate economics, William Nordhaus

1. Introduction

The thirtieth United Nations Convention on Climate Change (COP30), in Belém, Brazil, brings with it a great evolution in economic thinking, but above all, the host country brings more pragmatic proposals for practical economic actions to deal with the challenge and urgency that the climate crisis imposes on humanity. In this context, climate economics is the bridge between science and mitigation and adaptation policies, translating scientific predictions about physical systems into projections about economic growth and societal well-being.

William Dawbney Nordhaus had already realized in the 1970s, 20 years before ECO 92, that this would be a significant challenge to address, leading him to become the main precursor of this new branch of economic thought: climate change economics. Gradually, Nordhaus laid the foundations for this new branch of economics, albeit controversially, but confident that responses to these challenges could be found using neoclassical microeconomic tools, traditional macroeconomics, and the scientific foundation already available in the 20th century.

Nordhaus 's scientific output sparked heated debates, the most emblematic of which was his duel with Nicholas Stern. Many of the clashes centered on the intergenerational determinants of climate change, which still often leads to heated discussions replete with *trade-offs*. Perhaps that's why they're so intriguing to economists, with significant implications for the resulting economic modeling, which seeks to measure its effects on human well-being and the maintenance of human life, mitigating and adapting to climate change. Nordhaus's and Stern's work have motivated the definition and design of mitigation policies around the world to this day. They are, in practice, the expression of the most genuine application of economic science dedicated to solving the greatest externality humanity has ever faced.

Thus, this article seeks to address how a nascent climate change economy is forging its path in developing responses to the climate crisis. It covers the evolution of scientific thinking around global warming to the conception of accelerated climate change, including the *tipping points* and economic theoretical foundations of economics of climate change. It then seeks to present how Nordhaus 's school of modeling and his seminal work provided the theoretical foundations for the various typologies of economic modeling for climate change in the 21st century. Finally, it also highlights the main theoretical and ethical controversies in the Nordhaus versus Stern models.

2.1 *From Global Warming to Climate Change*

The technical-scientific journey that the climate economist underwent to develop the first economic models integrated into the climate issue is closely related to the evolution of studies by the Intergovernmental Panel on Climate Change (IPCC), which today guide discussions on climate change (RONCALLI, 2025).

Views on global climate change range from pessimistic to naive, denying the existence of global climate change or even embracing it (LESSER, 1995)**.** From this perspective, the section begins with the idea of a simple change in gas concentrations and some thermal effect, leading to a transition toward a new era, the Anthropocene, in which climate change leads us to a point of no return. This movement marked not only the evolution of science but also of economic thought, transforming what was known as environmental economics into the definition of Climate Economics.

2.1.1 *Scientific Basis for the Evolution of Economic Thought*

The Earth planet's environment has remained exceptionally stable over the past 10,000 years. This period of stability—known to geologists as the Holocene —has seen human civilizations emerge, develop, and thrive. Since the Industrial Revolution, a new era has emerged, the Anthropocene, in which human actions have become the primary driver of global environmental change (ROCKSTRÖM et al., 2009).

This path originated in the idea that Earth's warming was due to the accumulation of carbon dioxide (CO_2) and greenhouse gases (GHGs). The GHG effect led to the conclusion that climate change is underway and that humans have the power to influence and accelerate the entire process. This knowledge is credited to the findings of notably scientists: Eunice Newton Foote, Guy Stewart Callendar, Charles David Keeling and Wallace Broecker. Eunice Newton Foote published an experiment demonstrating that water vapor and CO_2 absorbed heat from solar radiation three years earlier, in 1856, but this work was only rediscovered in 2011, when the origin of GHGs began to be re-discussed (ORTIZ and JACKSON, 2022). Thus, the concept of the atmospheric greenhouse effect precedes the concept of "global warming" (RONCALLI, 2025).

However, it was Guy Stewart Callendar who linked the increased burning of fossil fuels to rising global temperatures in 1938. He estimated a global temperature increase of about 0.25°C over fifty years and demonstrated that the concentration of CO_2 in the atmosphere increased by 10% during the same period. Callendar associated this increase in concentration with the burning of fossil fuels, known as the “Callendar Effect” which links global warming to the artificial production of CO_2 by humans. Just with Roger Revelle that the average lifetime of a CO_2 molecule in the atmosphere was defined around 10 years before being dissolved in the ocean. This resistance to absorption by the ocean became known as the "Revelle factor". Revelle was also responsible for inviting Charles David Keeling to measure atmospheric $_{CO2}$ with the lowest possible noise (error), giving rise to the " Keeling Curve" in 1958. From then on, Keeling collected this information until his death in 2005 (RONCALLI, 2025).

Even with all this scientific development on the dynamics of gases in the atmosphere, in the 1970s, the effects of atmospheric CO_2 accumulation were not known with certainty, but two general effects were believed: the effect on climate through the GHG; and because of selective radiation filtering, was believed that increased CO_2 would lead to an increase in the planet's surface temperature (NORDHAUS, 1975).

It was, however, with Wallace Broecker that the effects of GHG accumulation became well-established. Work on the role of the oceans in climate change, the global ocean circulation map, and radiocarbon dating are considered the foundation of carbon cycle science. Although the term "global warming" appeared less than 10 times before 1975, many research papers used the term extensively after its publication. Thus, between 1975 and 1980, approximately 2,500 scientific articles referred to global warming (RONCALLI, 2025).

As early as the 1980s, Broecker and other scientists warned politicians about the dangers of climate change. Between 1984 and 1988, Broecker declared CO_2 the number one long-term environmental problem, summarizing it into three main conclusions: (i) the Earth is hotter than at any other time in history; (ii) global warming is significant enough that we can attribute, with a high degree of confidence, a cause-and-effect relationship with the GHG effect; (iii) GHG effect is significant enough to begin affecting the likelihood of extreme events (RONCALLI, 2025).

In 1988, climate change began to become a political issue when the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC). The purpose was to provide policymakers with regular scientific assessments of climate change, its impacts, and potential future risks, as well as to recommend options for adaptation and mitigation (RONCALLI, 2025). IPCC assessments have become the most reliable source of scientific evidence for climate negotiations held under the United Nations Framework Convention on Climate Change (UNFCCC) (FOSTER et al., 2024).

Based on the IPCC assessments, Rockstrom et al. (2009) proposed a *framework* based on planetary boundaries, whose essence defines a safe operating space for humanity related to the planetary system and its biophysical subsystems. However, in addition to CO_2, planetary boundaries involve: ozone depletion, increased atmospheric aerosol, ocean acidification, freshwater changes, Earth system changes, climate change, changes in biogeochemical fluxes, the introduction of new entities; and changes in the integrity of the biosphere. Of these nine, seven will have already been crossed by 2024 (KITZMANN, 2025).

In this sense, early attempts to define an upper limit for climate change focused on the rate of global warming. The world should warm no faster than 0.1°C per day, approximately equal to the natural variability of the global climate. The famous 2.0°C target is an arbitrary target, set by 11 German professors, adopted in 1995 by the Scientific

Advisory Board on Global Environmental Change of the German Federal Government (WBGU) for lack of an alternative (TOL, 2019).

However, it was actually Nordhaus who first suggested that the global average surface air temperature should not exceed 2°C above the pre-industrial period. He did this in the *Cowles Foundation Discussion Paper*, of 1975, by postulating that if the global temperature were higher than this, we would have climate outside the range of observations over the last hundred thousand years, but soon abandoned arbitrary targets in favor of cost-benefit analysis (TOL, 2019). The global surface temperature in the 2001-2020 was already 0.99°C higher than in 1850-1900, an increase in over 20 years faster than any other 50-year period in the last 2000 years (IPCC, 2023).

In this context, the climate change indicators assessed by the 6th IPCC Report (IPCC, 2023) only covers 2020. Then, when updated, using the same methodology, and replicated for a longer period, the average warming observed in the decade 2014-2023 rises to 1.19°C. For the single-year average, human-induced warming reached 1.31°C in 2023, compared to the period 1850-1900. Thus, human-induced warming has increased at an unprecedented rate in the instrumental record, reaching 0.26°C per decade in the period 2014-2023. The rate of global warming accelerated in 2023, and may not be temporary, surpassing the 1.5°C threshold soon. Thus, society lives life on the statistical tail, in which warming can now trigger several climate tipping points (TRUST et al., 2024; FOSTER et al., 2024). The disconnection between current net-zero carbon budgets and the 1.5°C target is evident. Carbon budgets need to be recalibrated, given the uncertainties and low probability of trend reversal (TRUST et al., 2024).

The study of this threshold and the environmental stress of the so-called tipping points, has allowed us to identify that the ultimate risk is that they disintegrate of the Earth system, creating a growing momentum that undermines our collective ability to deal with the vicious cycle of increasing consequences (LENTON et al., 2023). Even with the solid scientific basis, the lesson remains: dealing with the challenges of global warming is a daunting task for both scientists and economists, who need to understand future changes, and for policymakers, who must choose policies to balance risks and costs (NORDHAUS, 1994). Thus, questions like, "Is global warming real? Does it matter? What does it mean for society?" can be answered with a resounding yes: it is real, it matters, and it means we are beginning to face little-understood risks (NORDHAUS, 2013).

There is no more complex political issue to analyze than global climate change. Climatic dynamics are extremely complex, while the scope of the political issues raised, encompassing economic, ethical, social, and even political aspects, seems limitless. Views on global climate change range from pessimists who predict, and perhaps even long for, the eventual end of humanity; to pessimists and naive people who deny the existence of this one or even embrace it *(LESSER, 1995)***.** It was through this long journey that global warming science reached a consensus on the high probability of a substantial increase in temperatures in the 21st century. However, nations have taken only limited action to reduce GHG emissions since the first Kyoto agreement in 1997, and little progress has been made (NORDHAUS, 2010).

2.1.2 *Evolution of Economic Thought*

Marshall (1890) dealt with externalities and market failures and Pigou (1920) was the first to carry out a systematic analysis of pollution as an externality (PERMAN et al., 2011). The application of a Pigouvian tax, as defined in Pigou (1932), is an intervention strategy aimed at establishing a price for pollution (RONCALLI, 2022; TOL, 2019; HASSLER, KRUSELL and SMITH, 2016; PERMAN et al., 2011), the essence of which is the formulation of the polluter pays principle (STERNER and CORIA, 2012). If externalities exist, the market equilibrium is not Pareto optimal. An externality is an unintended, uncompensated impact on a third party (TOL, 2019).

In this sense, the economic theory underlying global warming is based on the concept of negative externalities, according to Nordhaus (1991), Pizer (1999), and Stavins (2007). A carbon price, then set based on the social cost of a ton of carbon emissions, must be imposed to correct market failures caused by externalities. Within the same framework, a model with a zero discount rate leads to a more stringent policy proposal (STERN 2006; SEO, 2013).

In this way, there are four fundamental characteristics of climate change that pose unique challenges for economic theory, requiring the extension of economic analysis into uncharted territory (AGLIARDI, CASARI and XEPAPADEAS, 2020; ACKERMAN and STANTON, 2013; NEWELL, PIZER and RAIMI, 2012; GOULDER and PIZER, 2006; STERN, 2007): i. the extent and nature of uncertainties; ii. the long time periods involved; iii. the international scope of the problem's causes, consequences, and solutions; and iv. the uneven distribution of policy benefits and costs across space and time.

However, by the end of the 1960s, the neoclassical economic main stream did not recognize the possibility of environmental constraints on the efficient functioning of markets. It was through the principle of material balance that both pollution and the extraction of natural resources were adequately addressed. These two aspects defined neoclassical environmental economics into two branches of research: i. natural resource theorists; and ii. pollution theorists. The latter primarily relied on static competitive general equilibrium (CGE) models (MUELLER, 2012).

Climate change economics arguably begins with Nordhaus (1982), focusing on diagnosing the economic underpinnings of climate change and offering positive and normative analyses of policies to address the problem. Although it overlaps with other areas of environmental economics, it has a unique focus due to the distinctive features of the climate problem—including the long timescale, the extent and nature of uncertainties, the international scope of the issue, and the uneven distribution of policy benefits and costs across space and time (GOULDER and PIZER, 2006).

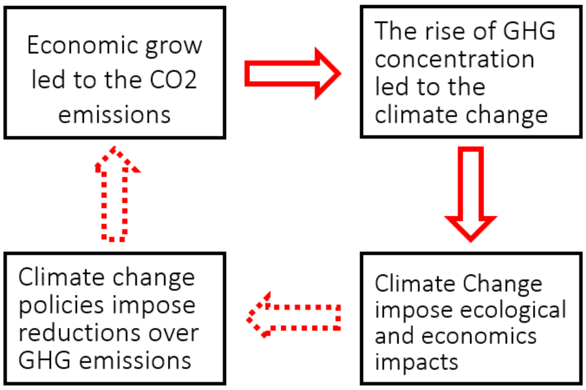
The initial discussions on the discount rate and intertemporal equity in climate economics were framed by a chapter in the IPCC Second Assessment Report, written by six prominent economists, including Kenneth Arrow and Joseph Stiglitz. They introduced the basic distinction between "prescriptive" and "descriptive" approaches. The prescriptive approach assumes that discounting future costs and benefits is an ethical issue; the appropriate discount rate should therefore be deduced from first principles, focusing on the utility of current versus future consumption. The basis of this approach, attributed to Ramsey (1928), is an argument demonstrating that, along an optimal growth trajectory, the discount rate for consumption equals the productivity of capital. Later mathematical analyses led to the formalization of this principle in what is often called the "Ramsey equation" (ARROW et al., 1996; *ACKERMAN and STANTON, 2013)*

Furthermore, according to UNFCCC (1998) and MacCracken et al. (1999), approaches without broad global participation would be ineffective in stopping GHG emissions due to the so-called "leakage effect", which results in losses in industry competitiveness due to the increase in total costs plus abatement costs; and generate the immigration of carbon-intensive industries to countries with more liberal environmental control policies, the “pollution heaven hypothesis” (BARKER et al., 2007; FRANKEL, 2009; SEO, 2013).

Thus, Nordhaus (1994) observes that, even with great technological advances and strict controls, the momentum of past GHG emissions, combined with great inertia in climate change policy, will lead to an inevitable encounter with massive climate change. The problem of global warming begins with economic growth and distorted market price signals, which lead to rapidly increasing CO_2 emissions into the atmosphere. CO_2 concentrations and other forces lead to major changes in the climate system, producing impacts on human and natural systems. Based on this, Nordhaus (2013) organizes the Figure 2 cause and effect scheme of society's responses to the threat of climate change, in which the arrows represent the links between the different parts of the economy-climate-impacts-politics-economy nexus.

However, the last two dashed arrows were presented at that time as a question mark, since such connections were not yet as evident as they are today, considering the lack of effective international agreements to limit emissions, given that there is only a Kyoto Protocol (a book of good practices, without sanctions). As Nordhaus (2013) warns, if we continue the current path of virtually no policy, the dashed arrows will become effective and the globe will continue on the dangerous path of unbridled global warming.

Figure 2. Circular flow of climate change science, impacts and climate policies.



Source: Adapted from Nordhaus (2013).

This contempt of the main economic stream for environmental issues and their impacts on well-being, highlighted by Nordhaus (2006), are evidenced in Munasinghe (2002) when he highlights that policies to solve macroeconomic and sectoral issues are not explicitly aimed at sustainability. The book "Macroeconomics and the Environment" reviews key articles published between 1970 and 2001 to trace the evolution of economic thought regarding the interconnection between macroeconomics and the environment. However, climate change was mentioned only once, and even then, without indicating that the phenomenon was a relevant externality. Furthermore, the main works addressed the fundamentals of economic growth and how the scarcity of natural resources could impact their dynamics, or even how long it was viable to continue extracting them: Leontief (1970), Koopmans (1973), Stiglitz (1974), Daly (1991) and Solow (1993).

Despite the main contempt stream, Nordhaus was a visionary. Nordhaus (1975) produced the first calculation of the external costs of air pollution from an extra unit of CO2 released into the atmosphere and the first carbon price scenarios up to 2095. This was the first time that the linear optimization calculation of the shadow carbon price was implemented for a Business as Usual (BAU) scenario—that is, a scenario in which nothing is done to control emissions, thus setting the shadow price equal to zero and other scenarios with assign social costs to the economic sectors. However, it was only in the 2000s, even with the effects of the climate crisis not yet so evident, that "exacerbated" or "enhanced" global warming, as it was called at the time, brought to the forefront economic stream concerns surrounding the challenges, which were already noticeable, as we can see in Spash (2004) and Stern (2006).

Thus, climate analysts no longer have any doubts about humankind's contribution to global warming, as consistently demonstrated by the 5th IPCC Report (IPCC, 2013). This understanding is fundamental to understanding that humankind is accelerating global warming from a geological scale to a generational scale, leading to climate change. This narrative shift is reinforced by the definition of *tipping points*, by Rockstrom et al. (2009).

Climate economics tends to lag behind climate science, especially the economics literature. Furthermore, climate economics has often been hampered by its uncritical adoption of a traditional cost-benefit framework, minimizing or ignoring the profound theoretical problems posed by uncertainty, intergenerational impacts, and long-term technological change. Then, it has transformed the economists' perspectives and prompted the emergence of new branches of economic thought and research. However, their assertions bear the hallmarks of an economics that seeks supremacy over other sciences, even basic science. Nevertheless, they still argue for a preponderance of theoretical weaknesses in neoclassical welfare and environmental economics over the results obtained from their models, such as those conducted by Nordhaus. The Stern (2006) led to the rethinking of climate economics (ACKERMAN and STANTON, 2013).

However, further evidence is that scientists and economists have made significant progress in understanding the science, technologies, and policies for mitigation, but not enough to produce effective results. The Kyoto Protocol was not economically attractive. This led to the United States withdrawal in 2001 and no accession from non-obligated countries. Emissions grew in these countries, especially China. The Protocol was initially designed to cover 63% of global emissions, and in practice, by 2012, it represented one-fifth of that. Even if it were extended, the impact would be limited, leading to a silent death, unnoticed and mourned by few, in 2012 (NORDHAUS, 2017).

Thus, nations fought in a series of conferences to reach the current Paris Agreement in 2015. However, this approach will not yield better results, due to countries tendency towards *free rider*, taking advantage of others efforts to dispose of global public goods. The "Climate Club" model would be the most fruitful approach to overcoming this parasitism, but it would also be insufficient, if price agreements around an internationally harmonized minimum carbon price are not established. This combination will likely be the most effective way to organize an international club agreement (NORDHAUS, 2017).

2.2 *Economic Modeling of Climate Change*

Given this climate economics journey, estimating the macroeconomic implications of climate change impacts and adaptation options is a topic of intense research, aimed at achieving low-emission economic development goals. To this end, it is necessary to understand how the uncertainty of these changes will translate into biophysical impacts, such as changes in agricultural productivity, which in turn will influence economic outcomes (ABALO et al., 2025).

An economic model of climate change needs to describe three phenomena and their dynamic interactions: i. economic activity; ii. carbon circulation (carbon budget); and iii. climate dynamics. From a modeling perspective, it is convenient to view the three phenomena as distinct subsystems (HASSLER, KRUSELL, and SMITH, 2016).

In this sense, there are two best-known approaches to climate modeling: “bottom up” (BU) and “top down” (TD). In calculating control costs, the BU approach derives from the use of detailed models of the cost of controlling GHGs. The TD approach derives from the observation of behavior as relative prices change. The distinct BU and TD approaches have their origins in energy modeling (KOOTEN, 2013; GOULDER and PIZER, 2006; HOURCADE et al., 2006; KOLSTAD and TOMAN, 2005).

The TD/BU debate first gained prominence during the efficiency gap discussions of the 1980s and 1990s (GRUBB et al., 1993). TD modelers (notably general equilibrium models - GGE) generally work with the assumption that competitive markets allocate all inputs and final goods efficiently. This denies the existence of energy efficiency gaps that society could profitably address. On the other hand, BU models suggested "no-regrets" possibilities for increasing energy efficiency in the economy. This divergence of views has not yet been fully resolved, and it has significant relevance for energy policy (HOURCADE et al., 2006).

Conventional BU models have described current and prospective energy technology competition in detail, both on the supply side and on the demand side. These models have been useful for illustrating future technology possibilities, with distinct environmental impacts. BU models are detailed and include the physical and chemical equations that affect ocean and atmospheric circulation and other relationships. They tend to be multilayered, with information passed from lower to higher levels. Thus, any uncertainty at one level is passed to another and, due to the model's structure, is subsequently amplified. The final model results— macroscale results —less reliable than results at lower levels—microscale results (KOOTEN, 2013; *HOURCADE et al.; 2006*).

Criticisms of BU models lie in their failure to provide a realistic portrayal of microeconomic decision-making by firms and consumers when selecting technologies, or of the macroeconomic feedbacks of different energy pathways, policies *and changes in commodity prices*, in terms of changes in economic structure, productivity, and trade that would affect the rate, direction, and distribution of economic growth. Conventional BU models tend to suggest that efforts to replace specific forms of energy or to reduce GHG emissions would be relatively inexpensive and, in some cases, even profitable (HOURCADE et al., 2006; *GOULDER and PIZER, 2006*)**.**

At the other extreme are conventional TD models that address the consequences of policies in terms of public finances, economic competitiveness, and employment. Since the late 1980s, TD modeling of energy economic policies has been dominated by computable general equilibrium (CGE) models, reflecting the declining influence of other macroeconomic paradigms, such as disequilibrium models (HOURCADE et al., 2006).

In 2010, CGE modeling celebrated its 60th anniversary, marked by a celebration in Oslo commemorating the 1960 publication of Leif 's A Multi-Sector Study of Economic Growth. Johansen, which is recognized as the first CGE model. It is worth noting that the model is distinguished from other economic models by the explicit identification of the behavior of economic agents separately (DIXON & JORGENSON, 2013).

Given the experiences with TD, CGE models were assumed to represent the real-world microeconomy and its responsiveness to policies, such as the substitutability of energy with other inputs or even substitution between consumer goods. However, what TD models in general tend to lack, is technological flexibility beyond current practice, since input substitution elasticities are critical to technological response. Estimated from historical data, they do not guarantee valid parameters in a future with ambitious climate policies and induced technical changes (HOURCADE et al., 2006).

In the modelers' journey toward using TD, those employed for energy purposes stand out, such as the International Energy Agency (IEA), has provided medium to long-term energy projections since 1993. In 2021, a new IAM framework was adopted, combining the two previous models into the Global Energy and Climate Model (GEC) to develop energy system forecasts, with net-zero emissions by 2050, detailed sector-by-sector and region-by-region (IEA, 2024).

Over the past thirty years, many IAMs have been developed to estimate the impact of economic development on the environment. The central economic model is Nordhaus's (1993) DICE model, a reference for the IAM (BOVARI, GIRAUD and ISAAC, 2018). A scenario framework has been established by the research community to support climate change IAM analysis, organized around three main dimensions: (i) the extent of climate change that is described by the scenarios Representative Concentration Pathways (RCPs), which quantify the range of potential future GHG emissions; (ii) possible future socioeconomic conditions, described as five Shared Socioeconomic Pathways (SSPs), which depict different socioeconomic projections and the challenges they pose for mitigation and adaptation; and (iii) climate policy applications, described as Shared Climate Policy Assumptions, which capture key attributes of climate policies, including targets, instruments, and obstacles (BANERJEE et al., 2020).

SSPs were designed to represent different climate mitigation and adaptation challenges. The underlying narratives and quantifications of each SSP also encompass a wide range of economic, social, institutional, and organizational variables. However, using global SSP pathways to project changes in natural capital at a localized scale simplifies local social, economic, and ecological feedbacks, as well as land-use dynamics (BANERJEE et al., 2020).

However, this scenario-defining logic differs somewhat from the traditional logic outlined in the Fifth Assessment Report (AR5), which defined a standard for projections, including new models and a more complete representation of radiative forcing and new Representative Concentration Pathways (RCPs). Based on the total radiative forcing (RF) in 2100, the concentration-based RCPs and global mean surface temperatures for 2081–2100, relative to 1986–2005, would likely be in the range 0.3°C to 1.7°C (RCP2.6), 1.1°C to 2.6°C (RCP4.5), 1.4°C to 3.1°C (RCP6.0), and 2.6°C to 4.8°C (RCP8.5) (IPCC, 2013).

The Sixth Assessment Report (AR6) assessed the climate response to five illustrative scenarios that cover the range of possible future developments in anthropogenic climate change drivers found in the literature. These scenarios begin in 2015 and include the five scenarios: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, in the following forms: with high and very high GHG emissions (SSP3-7.0 and SSP5-8.5) and CO2 emissions that nearly double from current levels by 2100 and 2050, respectively; scenarios with intermediate GHG emissions (SSP2-4.5) and CO2 emissions remaining around current levels until mid-century; and scenarios with very low and low GHG emissions and CO2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO2 emissions (SSP1-1.9 and SSP1-2.6) (IPCC, 2021).

IAMs can then be defined as approaches that integrate knowledge from multiple domains into an internally consistent framework. Their strength lies in their ability to estimate the social cost of carbon emissions (SC), to solve cost-effective policy problems, and to assess the costs and benefits of mitigation scenarios (BARRAGE and NORDHAUS, 2024; NORDHAUS, 2017; NORDHAUS, 2001).

Thus, IAMs seek to balance the costs and benefits of measures. These models are essentially mathematical optimizations with the imposition of constraints how a temperature below 2° C. Thus, the present (discounted) value of social welfare is maximized, subject to dynamic and static constraints representing potential damages, production possibilities, and interactions between markets and regions of the world. The objective function includes consumer and producer surpluses, the potential damages of global warming as a function of temperature, and mitigation costs (BARRAGE and NORDHAUS, 2024; KOOTEN, 2013).

Cost-Benefit Analysis (CBA) aligns the potential Pareto gain of a project/policy with a descriptive approach to determine a number for the discount rate. " r" could be a rate of return (free of financial risk), reflecting a level that reflects people's propensity to trade consumption in the present for future consumption. To test well-being, there is a tendency to adopt the prescriptive method, considering the following composition: where ρ is the discount rate of utility, η is the elasticity of the marginal utility of consumption, and g is the economic growth rate. Some economists prefer to select the values of ρ e α from observable behaviors. Others prefer to define them based on ethical considerations. The controversy surrounding the Stern Report lies in the prescriptive choices made, with the value of r being 2.1%, based on the definition of $\rho = 0{,}1$ e $\alpha = 1$ and g = 2% (ESPAGNE et al., 2018; PERMAN et al., 2011).

$$r = \rho + \alpha g$$

IAM models are used to develop long-term emissions projections and socioeconomic scenarios assessed by the IPCC (BATTISTON et al., 2021). In practice, IAMs for climate change have their roots in cost-benefit analysis (CBA), which involves a broad set of techniques initially developed to evaluate projects limited in scale, geography, and time, and which have been extended to cover more complex applications (MUNASINGHE et al., 1995). IAMs can be divided into two model general classes: policy optimization and policy evaluation (BARRAGE AND NORDHAUS, 2024).

IAM models were initially designed for policymakers to assess different tradeoffs and policy implications. Composed of several sub models, they aim to provide a detailed view of the future across multiple dimensions, from energy systems to socioeconomic developments. Now, IAM scenarios are being used by financial institutions and supervisors to assess climate risks (CARLIN et al., 2022).

Better metrics and financial macro-models are needed to inform policy. Metrics for defining what is green and what is not must be transparent, science-based, and not subject to political sentiment. Assessing climate risk exposure using only metrics based on GHG emissions (e.g., emissions intensity) and physical risk using aggregate scores can lead to risk underestimation and greenwashing, increasing financial risk (De ANGELIS & MONASTEROLO, 2024).

Emissions vary across scenarios depending on socioeconomic assumptions, levels of climate change mitigation, and, for aerosols and non-methane ozone precursors, air pollution controls (IPCC, 2021). When macroeconomic CGE or DSGE models are used by central banks and financial supervisors, they reduce climate complexity by using exogenous frictions. However, they fall far short of adequately capturing the impacts of climate risks, their actual tradeoffs, and potential solutions. Poor risk assessment and opportunities (co-benefits) lead to ineffective policies and resource use, creating new unproductive debt (public or private) and thus increasing financial risk (BATTISTON et al., 2021).

Macro-financial models used for economic policy should evolve to capture climate risk characteristics such as nonlinearity, tail risk, and out-of-equilibrium dynamics, specific risk transmission channels, and macro-financial feedback. They should allow agents to move away from forward-looking rational expectations and incorporate adaptive expectations. Consistent Stock-Flow Consistent (SFC) models are complementing the standard models (De ANGELIS & MONASTEROLO, 2024), as in MAZZOCCHETTI et al. (2025).

The solution is proposed in which an IAM generates economic output trajectories under climate policy scenarios. A second climate financial risk model (CFR) uses the IAM results to calculate interest rates for firms using different energy technologies (k). Investor expectations and climate value-at-risk (ClimateVaR) determine the allocation of capital among technologies. The IAM is then updated to reflect the diversity in financing costs (BATTISTON et al., 2021).

Given the evolution of IAMs, it is possible to understand that economic modeling for climate change and in turn *climate economics* drew on neoclassical environmental economic theory of externalities, welfare economics translated into cost-benefit analysis, and macroeconomics translated into TD models. In this context, Nordhaus developed his school of climate modeling in the first time.

2.2.1 Nordhaus School of Economic Modeling

Nordhaus graduated from Yale University in 1963 and received his Ph.D. from MIT in 1967. He then became a faculty member at Yale. Nordhaus is a skilled modeler and was a pioneer in the development of techniques for the analysis of exhaustible resources (KURTZ, 2014). In 2018, he received the Nobel Prize in Economics along with Paul Romer, recognized by the Prize Committee for their contributions to integrating climate change into long-term macroeconomic analysis, as well as the analysis of market failures for the development and extension of neoclassical growth theory (KELLEHER, 2019).

Nordhaus school of economic modeling is the common use among modelers of quantifying the damages of climate change externalities as a proportion of GDP (HASSLER, KRUSELL and SMITH, 2016). The first steps towards the development of modern integrated assessment appear in Nordhaus (1977) (HASSLER, KRUSELL and SMITH, 2016). However, it was only with the seminal DICE model, in Nordhaus (1994), that the problem of climate change mitigation was incorporated into an optimized economic growth framework. Nordhaus (1994) treats mitigation as part of an optimal capital accumulation strategy, whether in the form of productive capital or climate capital. The trade-off depends on mitigation costs, climate damage, marginal productivity of capital, among others. (ESPAGNE et al., 2018).

Most economic analyses of global warming have focused on estimating the cost of reducing emissions of carbon dioxide and other greenhouse gases, typically applying energy economics models, e.g., Manne and Richels (1991) and Jorgenson and Wilcoxen (1990). Nordhaus (1991) went further and examined the optimal degree of reduction, also considering the benefits of preventing damage and concluded that only modest action is justified (CLINE, 1992).

The first integrated climate-economy models were deterministic how Nordhaus (2008). These models did not allow for adequate consideration of risk and uncertainty in planners' decisions, even when Monte Carlo analyses were conducted (CROST and TRAEGER, 2013). Contributions to the modeling of endogenous catastrophic environmental risk were mainly stylized (FILLON, GUIVARCH and TACONET, 2023).

Nordhaus (2019) names the beginning of his work with IAMs in the form of simple energy/climate models, Nordhaus (1975; 1977). These models were discarded in favor of other approaches, such as a small macroeconomic model (Nordhaus and Yohe 1983), a static model with a damage function (NORDHAUS, 1990) and finally, in Nordhaus

(1992, 1994) I found a model that captured all parts of the DICE model (Dynamic Integrated model of Climate and the Economy). *Managing The Global Commons* (NORDHAUS, 1994) provides the DICE, the first dynamic model to include a closed-loop system encompassing emissions, concentrations, climate change, damage, and emission controls. It is useful for estimating the costs and benefits of different mitigation scenarios and analyzing the impact of control strategies over time, with new techniques and results on the role of uncertainty and the "risk premium" involved in climate policies.

DICE model shows that the value of additional information is significant, suggesting a significant benefit from further research on climate change and that existing uncertainties justify higher carbon taxes and increased GHG emission control rates. He also highlights the crucial importance for overall economic efficiency of how the revenues collected are used. He finds that the level of the carbon tax changes little with the arrival of new information and regardless of future mitigation efforts, past GHG emissions have already condemned us to future climate change, and therefore, adaptation to a new climate is imperative (NORDHAUS, 2019)..

Nordhaus's DICE model is a Ramsey-Cass-Koopmans approach. It assumes a closed economy with a constant return to scale, Cobb-Douglas technology, combining labor and capital, where agents' decisions are made under perfect forecasting. In the steady state, output increases in step with labor force growth and technological progress, while factor costs adjust so that all markets equilibrate and prevents situations such as mass unemployment and over-indebtedness (BOVARI, GIRAUD, and ISAAC, 2018).

The most recent full version of the DICE model is Barrage and Nordhaus (2024), but DICE2016-R2 has much the same structure as the first version, but has revised each of the major sectors in small or large ways. The evolution of the DICE model 1992–2016 is reviewed in Nordhaus (2018). There are many versions of DICE. Nordhaus began developing DICE with a simple energy/climate model in the 1970s (Nordhaus, 1977). The current format of the model can be found in Nordhaus (1992). Since this publication in Science, he has multiplied research projects on DICE. The ultimate goal of the DICE model is to calculate the social cost of carbon, which is the central pillar in the cost-benefit analysis of climate change policies (RONCALLI, 2022).

The basic structure of the DICE model is shown in Figure 2, that displays the logical circular flow from emissions to climate, to impacts, to policies, and back to emissions

(NORDHAUS, 2019). However, already in Nordhaus (2008) examines climate and economic uncertainties, concluding that economic factors are more important. He presents a small-scale Monte Carlo analysis with iterations, in which he allows eight parameters in the DICE to vary. The temperature change over this century is positively correlated with per capita consumption. This is because he allows for relatively large variation in economic growth but relatively small variation in climate impacts. High-growth scenarios have higher production and therefore higher emissions, leading to warmer temperatures (ACKERMAN and STANTON, 2013).

2.2.2 STERN Model

The Stern *Review* focused on the economics of risk and uncertainty, using economic tools to explain the challenges of climate change, a global problem with long-term implications. Must be emphasized the need for more work by scientists and economists to address the analytical challenges and resolve uncertainties, but it is already clear that the economic risks of inaction are serious. Stabilizing GHG concentrations is feasible, at significant but manageable costs, with existing policy tools, creating the incentives to change investment patterns and move the global economy on to a low-carbon trajectory and adapt to impacts that can no longer be avoided. Furthermore, reducing risks requires collective action and cooperation among countries through international frameworks, shared objectives, and public-private partnerships (STERN, 2006).

The Stern *Review* provides an extensive discussion of the ethical issues involved in discounting, arguing for a prescriptive approach with a near-zero value for δ, the rate of pure time preference. All people in current and future generations are of equal moral standing and deserve equal treatment, according to the Stern Review. A higher rate of pure time preference would inappropriately devalue future people who are not yet here to speak for themselves. Similar arguments date back at least to Ramsey and have been made by many economists and philosophers (ACKERMAN and STANTON, 2013).

At the same time, an exactly zero value for pure time preference is problematic for economic theory. With an unlimited time horizon, this would imply that the present value of future utility is infinite and that the current generation's well-being could be ignored as an extremely small part of the intergenerational whole. Stern's solution is to include a small probability that human society will not survive some unspecified cataclysm, arbitrarily set at 0.1 percent per year. This becomes the rate of pure time preference: since we are only 99.9 percent certain that someone will be around next year, the present value equivalent of the certainty of next year's well-being is 0.999 as large as this year's. There is a strong sense of Deus ex machina (or perhaps *diabolus ex machina*) on this solution, but it results in a low discount rate without setting pure time preference literally to zero (ACKERMAN and STANTON, 2013).

Stiglitz and Stern, along with other authors in Stiglitz et al. (2017), recognize that nations choose different instruments to implement their climate policies, always conditioned by national and local circumstances and the political support they receive. Explicit carbon pricing levels are desirable, as long as they are consistent with the Paris Agreement's goal of stabilizing average temperature anomalies well below 2°C. Furthermore, they emphasize that the misleading use of IAM models has led to debates about the correct social value of carbon and should be used to help ground climate actors strategies.

The use of the plural in reference to the valuation of carbon externalities is not anecdotal. The real policy implication of the Stern-Stiglitz report is to advocate for a plurality of carbon prices around a certain value corridor. Contrary to most proposals among climate economists, a single carbon price is not considered the ultimate rationale for climate mitigation actions. It is worth noting that such a global carbon price corridor is defensible and theoretically justified, rather than a single carbon pricing strategy (ESPAGNE et al., 2018).

IAMs can help implement SCC corridors. There is indeed a broad consensus among climate economists to consider climate change a global externality that must be contained. Therefore, basic public economics wisdom calls for some mitigation efforts (IPCC, 2014). But there appears to be no consensus on the value of the carbon externality. As Stiglitz et al. (2017) write, “although there is consensus among models on the technical changes needed to keep climate change below 2°C, models cannot agree on the carbon price needed to trigger these changes.” The IPCC (2014) provides prices ranging from \$15 to \$360 per tCO2 in 2030, and from \$45 to \$1000 per tCO2 in 2050 (in 2005 US dollars) (ESPAGNE et al., 2018).

In theory, market-based regulatory instruments correct market failures at the lowest cost. However, evidence on their effectiveness remains scarce. The European Union

Emissions Trading System (EU ETS)—the world's first and largest market-based climate policy—induced regulated manufacturing firms to reduce carbon dioxide emissions by 14–16% without detectable contractions in economic activity. There is no evidence of outsourcing to unregulated firms or markets; instead, firms made targeted investments, reducing the emissions intensity of production. These results indicate that the EU ETS induced global emissions reductions, a necessary and sufficient condition for mitigating climate change (COLMER et al., 2024).

Stern, Stiglitz and Taylor (2022) argue that there are two critical questions facing the world in responding to the challenges of climate change. First, how aggressive should we be in combating climate change—what should our goals be? Second, how best to achieve these goals—how will our economy need to change, and what are the best instruments to induce these changes? There is a shared understanding that this will involve fundamental structural change in our economies, including key energy systems, transportation, cities, and land. And there is broad consensus to use a wide range of measures, including carbon pricing, green investment programs, systems design or reform programs, capital market interventions, and standards and regulations, as reflected in the Stern-Stiglitz Commission Report (2017), the IEA (2021), and the IMF (2021). Furthermore, despite their dominance in the economic literature and their influence on public debate and policymaking, the methodology used by IAM rests on flawed foundations, which become particularly relevant when considering the realities of the immense risks and challenges of climate change and the radical changes in our economies that a robust and effective response requires.

This consensus would be at odds with a broad current of thought within the economics profession and the economics of climate change has focused on IAMs. The use of standard IAMs, with their choice of calibration, has led some prominent economists to conclude that "social optimization" implies accepting a temperature increase of about 3.5–4 degrees Celsius (Nordhaus, 2018), an increase seen as catastrophic by many, especially climate scientists (STERN, STIGLITZ and TAYLOR, 2022).

Many critics, such as Nordhaus (2007), Tol and Yohe (2006), and Yohe (2006), have identified the low discount rate—much lower than rates conventionally used by economists or policymakers—as Stern's (2006) main weakness. Some have noted that Stern's near-zero rate of pure intertemporal preference, if used by individuals, would imply much higher savings rates than are actually observed (Arrow 2007; Weitzman 2007). Thus, if discount rates are consistent with actual saving behavior, the rate of pure time preference should be higher. In this context, Stern's very low rate of pure time preference has been described as paternalistic (Weitzman 2007; Nordhaus 2007) imposing its own ethical judgment on the revealed preferences of most individuals (ACKERMAN and STANTON, 2013).

2.2.3 Comparative View of the Nordhaus vs. Stern Models

Nordhaus established himself with the DICE model and Stern with the PAGE model. These models have practical similarities: (1) they are dynamic IAM models coupled with a macroeconomic module and a simplified climate model; (2) GHG emissions are considered as a product of a production function, which causes temperature increases and losses in a utility function; and (3) they use an isoelastic social utility function. However, there are also differences in the comparative perspective between the models, summarized in Table 1.

Table 1. Differences and similarities in Stern's and Nordhaus' models.

Variable/Parameter	NORDHAUS	STERN
Type of model	optimal dynamic IAM	stochastic dynamic IAM
Utility function U(C) = (C^(1−α)/1-α)	α = 2 in DICE	α = 1 in PAGE
Decision framework	One-shot decision	One-shot decision
Economic growth	g = 1.3%	g = 2.0%
Climate dynamics	Simplified carbon and temperature dynamics	Simplified carbon and temperature dynamics
Discount rate $r = \rho + \alpha g$	ρ = 1.5% leading to r = 4.1%	ρ = 0.1% leading to r = 1.4%
Abatement cost	BK = 1, 200$ in 2005, BK = 950$ in 2100	Average cost of mitigation: from 61$ in 2015 to 22$ in 2050
Climate sensitivity	3 ◦C as the mean value of [1.5 ◦C; 4.5 ◦C]	High + climate scenario [2.4 ◦C; 5.4 ◦C] with a fat tail probability distribution
Type of quadratic damage function	[1%; 5%] of GDP loss for a 4 ◦C increase	Same with possibility to integrate additional non market impacts.

World climate mitigation target	Low (25% global carbon emission reductions by 2050)	High (50% global carbon emission reductions by 2050)

Source: Modificated from Espagne et al. (2018), Wang et al. (2017) and Perman et al. (2011).

2.4. Climate Uncertainties and Risks

The uniqueness of the economic problem represented by climate change lies in the environment of uncertainty generated by the phenomenon, in which three conditions stand out that delimit probabilities and barriers to risk mitigation (WEITZMAN, 2009). First, decisions have impacts that are difficult to reverse and will be perceived and felt far into the future, which prevents adequate use of the concept of temporal discounting and choice of an interest rate. Second, the uncertain outcome of a stochastic process, with known structure and objective frequency probabilities, making it difficult to apply expected utility analysis (discounting the present). Third, the profound structural uncertainty in science, combined with the economic inability to meaningfully assess the catastrophic losses resulting from disastrous temperature changes, climate science seems to be saying that the probability of a disastrous collapse of planetary well-being is not negligible, even if this small probability is not objectively knowable.

Thus, making decisions about climate change requires an understanding of the impact of uncertainties, which complicate the decision-making process and limit decision-makers ability to identify the best options. In this environment, there are three main areas of uncertainty: scientific, socio-ecological, and socioeconomic (ARROW et al., 1996). First, scientific uncertainties obscure the relationships between GHG emissions and atmospheric concentrations, as well as the *feedback dynamics* climate vis-à-vis the effects of climate change on global temperature, ecological cycles, sea level and the occurrence of climatic events. Second, socioecological uncertainties obscure how climate change will affect the relationship between human societies and the biosphere, particularly where human well-being is strongly affected by nature. These relationships include agricultural production, fisheries, and the spread of disease. Third, socioeconomic uncertainties obscure the economic and social effects of climate change and its mitigation. These uncertainties, which affect the economic valuation of resources, international trade, technological change, and other socioeconomic interactions, are the focus of this volume.

Regarding scientific uncertainties, it is worth mentioning that, to date, not all CO_2 fluxes are equally well known, and attempts to understand regional contributions to each flux remain uncertain. We know fossil fuel emissions very well, down to the national level. However, CO_2 fluxes from land-use change are the most uncertain. There is also variability in these fluxes at the annual and decadal scales, for which we understand some of the drivers, but not all. However, long-term trends are better known and are the most important trends forpredicting climate change (FRIEDLINGSTEIN et al., 2023).

In Newell, Pizer and Prest (2022), the authors propose a new approach to defining discount rates for the Social Cost of Carbon (SCC). Amid uncertain economic growth integrated into a climate cost-benefit analysis, it is possible to derive discount rates endogenously, rather than assuming an arbitrary constant rate. Using the Ramsey formula, the authors chose parameters such that the implicit term structure of interest rates in the model aligns with real-world interest rate trends and uncertainties. Instead of a single fixed discount rate, the rule produces a decreasing term structure: higher rates in the short term and gradually lower rates in the distant future as uncertainty increases. This rate also takes into account the possible correlation between economic growth and climate damage: if climate damage hits low-growth states harder, the effective discount rate adjusts accordingly.

The SCC is notably higher using this discounting approach than under conventional discounting: about $78 per ton of CO2e in 2020, compared with about $42 using fixed rates. The new discounting rule alone would slightly reduce the SCC compared with using a constant 3% rate, as it still places a greater premium on the short term. Short-term discount rates may be around 3% to accommodate current financial market data, but impacts in the distant future actually attract lower rates, which partially explains the uncertainty and ethical weight of the impact on future generations. This could affect long-term investments, which need to internalize the long-term climate cost more and integrate climate risk into economic forecasts. However, this framework may not fully capture unexpected changes in productivity, demographics (NEWELL, PIZER & PREST, 2022).

Conclusion

Based on the theoretical framework that underpinned the work of William Dalbney Nordhaus, we sought to discuss the salient features of the models developed by the patron saint of climate change economics, as well as the controversies and debates with Nicholas Stern. In this sense, this paper traced the evolution of this new climate approach from traditional economic worldviews, seeking to consistently address the following question: is there an economy of climate change? This question was addressed through research vertical I: state of the art: proliferation of hypotheses in scenarios of uncertainty.

Nordhaus is recognized as a pioneer in the development of integrated economic assessment models (IAM) for climate policy. One of the most cited and often little-understood authors, he was the first to use macroeconomic tools integrated with temperature models to address global warming. Furthermore, Nordhaus established a school of thought, founded trends, and led epic debates. Nevertheless, considering science as the fruit of theoretical debate, one cannot ignore Nicholas Stern's role in the evolution of economic thought on the subject.

In the beginning, in the 1970s, 1980s and 1990s, the indication of the *main The early trends* in climate economics were toward GHG taxation, as can be seen in the recommendations compiled by Nordhaus (1975). Only after the start of *allowance* market experiments in the 2000s did the development of the remedy most widely used today by economies around the world begin. In this, the prescription of the emission permit market alternative is dominant, as is the voluntary carbon credit (offset) market, an alternative variant of GHG pricing without binding targets.

The perception is that the pricing of the negative externalities of climate change, via a price signal on GHG emissions, notably CO2 and methane, has also undergone an evolutionary process.

However, many mitigation policymakers are unprepared for the economic disruption this will bring. Poor modeling practices have led them to underestimate the economic losses from events that climate scientists consider likely. And even if economic loss estimates are revised upward, financial supervisors lack the prudential tools they need to prepare the financial system for them.

The evolution of climate economics has always followed paths grounded in the development of climate science. This scientific premise ensured that economic thinking, including the models developed, also follow the scientific method, organized in a systematic and replicable manner.

Throughout the 20th century, with the exception of the works of Nordhaus (1975) and Cline (1992), the economist was dominated by the discussion of obstacles to economic growth, distributive and equity aspects, as well as the potential and proven scarcity of natural resources and the limits of sustainability vis-à-vis unbridled population growth, as is clearly demonstrated in Munasinghe (2002).

Climate economics emerged in practice and became present only in the 21st century, when the effects of climate change became clearer and evidenced by the increasing costs and material damages of extreme environmental events and disasters. Thus, economists' attention to climate change stemmed from Nordhaus's seminal work. The COP30 carbon pricing club proposal, lead by Brazil and European Union, could be the first "Climate Club" model, that would be the most fruitful approach to overcoming the free rider parasitism. However, how highlited by Nordhaus (2017), it would also be insufficient, if price agreements around an internationally harmonized minimum carbon price in the rest of the world are not established.

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