Methodological analysis of environmental degradation and sustainability

Análisis metodológico de la degradación ambiental y la sostenibilidad

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ABSTRACT

The climate crisis represents one of the most significant challenges of our era and is increasingly linked to human activities. The objective of this work is to study the main methodologies researchers used to measure environmental degradation and sustainability in economic related studies. To this end, we conducted a bibliometric analysis to understand the current state of the main indicators of environmental degradation and sustainability used in economic research during the last 20 years. In addition, we conduct a historical review of how these concepts have evolved on the international agenda as reference for interpreting the biosphere integrity in international policy. Our results indicate that the most frequently used indicators are greenhouse gas emissions, carbon dioxide emissions, Ecological Footprint and Biocapacity. Additionally, our findings suggest a lack of a comprehensive methodology, which highlights the need to develop robust frameworks to guide public policy.

Keywords: environmental degradation, sustainability, methodological analysis, ecological footprint, biocapacity, CO_2 emissions.

RESUMEN

La crisis climática representa uno de los desafíos más importantes de nuestra era y está cada vez más vinculada a las actividades humanas. El objetivo de este trabajo es estudiar las principales metodologías que los investigadores han utilizado para medir la degradación ambiental y la sostenibilidad en estudios económicos. Para ello, realizamos un análisis bibliométrico con el fin de comprender el estado actual de los principales indicadores de degradación ambiental y sostenibilidad empleados en la investigación económica durante los últimos 20 años. Además, llevamos a cabo una revisión histórica de cómo estos conceptos han evolucionado en la agenda internacional como referencia para interpretar la integridad de la biosfera en la política internacional. Nuestros resultados indican que los indicadores más utilizados son las emisiones de gases de efecto invernadero, las emisiones de dióxido de carbono, la Huella Ecológica y la Biocapacidad. Asimismo, nuestros

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hallazgos sugieren la falta de una metodología integral, lo que subraya la necesidad de desarrollar marcos sólidos que orienten las políticas públicas.

Palabras clave: degradación ambiental, sostenibilidad, análisis metodológico, huella ecológica, biocapacidad, emisiones CO_2.

INTRODUCTION

Over the last century, the primary focus of societies has been promoting economic and social progress to raise living standards. In recent decades, technological advances have enabled human activities to overcome geographical barriers, fostering a global economy of interdependent nation-states. Yet, the climate crisis now presents one of the most pressing challenges to understand the relationship between biosphere integrity and human activity. Global socio-economic patterns can be studied from different perspectives within the fields of economics and international business. However, both disciplines face significant challenges in comprehending contemporary issues and developing effective solutions to actual global problems (Buckley et al., 2017).

In the early stages of the international environmental agenda, concern for natural resources focused primarily on food security and the availability of inputs for private agriculture, later expanding to resources needed to sustain production and consumption patterns. Although environmental protection was acknowledged, it was initially framed through a human-centered lens, viewing the environment as the space where people live and work—divided into natural and artificial components—primarily serving human needs and aspirations. Accordingly, humans were seen as stewards of natural resources, responsible for managing and, "whenever possible, restoring or improving the Earth’s capacity to produce vital renewable resources" (UN, 1972, p. 4). In this view, all natural resources existed to enhance human well-being, with restoration framed as conditional and economically ambiguous.

By the late 1980s, however, this perspective began to shift toward a more respectful approach to the environment, moving beyond the notion that nature exists solely for human use. Growing levels of environmental degradation made clear the urgent need for international cooperation and recognition of the global interdependence of ecological impacts—rendering isolated national efforts insufficiently. In the early 1990s, broader elements of biosphere integrity began to enter the conversation, although still mainly viewed through the lens of how they are affected by climate change, rather than as independently overused or in need of restoration. Up to that point, environmental action had largely focused on reducing pollution, with less attention paid to sustainable management, overexploitation, or ecosystem restoration.

With the emergence of sustainable development, reducing environmental degradation evolved from a matter of concern to a broader imperative. From an economic perspective, natural resources were once viewed as infinite, productive inputs that supported rising living standards. Over time, they came to be seen as finite, posing limits to development and even threatening those very standards. In the context of sustainable development, the notion of natural resources—implying purely productive factors—is increasingly replaced by the environment as the space that sustains human life, and more fundamentally, by biosphere integrity, which encompasses the health and stability of the planet’s life-support systems.

In summary, the discourse has shifted—from focusing on reducing environmental degradation or preserving resources for modern lifestyles—to recognizing that impacts on biosphere integrity pose a direct threat not only to production and consumption, but to human life itself. However, it is also acknowledged that there are still significant gaps in our understanding of how human activity affects various aspects of biosphere integrity.

Disciplines such as economics and international business use two key frameworks for studying the impact of cross-border human activities on ecosystems: environmental degradation and sustainability and their relationship with socioeconomic indicators. The former emphasizes negative impacts, while the latter considers nature's regenerative capacity.

Although both concepts have attracted growing attention and sparked a surge in related research. There is a lack of a holistic perspective on what are the different approaches and the most common ones used to interpret the impact of human activities on the environment in economic areas. This is because current research and similar studies focus predominantly on economic aspects, a regional sample or a partial aspect of environmental degradation or sustainability through specific indicators (Ahmad et al., 2020; Goh & See, 2021; Raza et al., 2024; Takam Tiamgne et al., 2022; Wu, 2022; Zhang & Deng, 2024; Xie et al., 2020). Current assessments focus on predicting or highlighting threats to current living standards. Therefore, assessing what are the main methodologies used to study the relationship between the environment and economic aspects, how well existing methods reflect the actual state of the environment, how these tools were developed, and what they omit represents a current knowledge gap. This knowledge gap leads to assessment results that are insufficient for accurate and effective environmental strategies. Therefore, this paper aims to answer the following research questions:

Q1 What are the most frequently used indicators in research to measure environmental degradation and sustainability in economic related studies?

Following the introductory section. This paper is organized as follows: The second section presents the bibliometric analysis conducted to identify the leading methodologies applied in literature related to environmental degradation or sustainability and economic aspects. Section 3 reviews the evolution of environmental issues on the international agenda, helping to contextualize how international policy has focused on several environmental aspects and offers a review on key aspects of selected leading methodologies that can be related to the changing international priorities. Finally, Section 4 closes with a conclusion of the major findings.

BIBLIOMETRIC ANALYSIS

Numerous scholars have examined the consequences of human actions on the environment, focusing on different consequences, disciplines and methods. But one of the fundamental steps in researching a subject is to understand the existing knowledge base of that time by conducting a literature review. All fields are adopting better methods with replicable, scientific and transparent processes (Paul & Barari, 2022). These processes, when used with improved databases and software, also show the evolution in researcher´s approach to one field. The primary objective of this study is to explore the landscape of academic production related to the principal methodologies used to measure the impacts of economic activities on the environment through a bibliometric analysis.

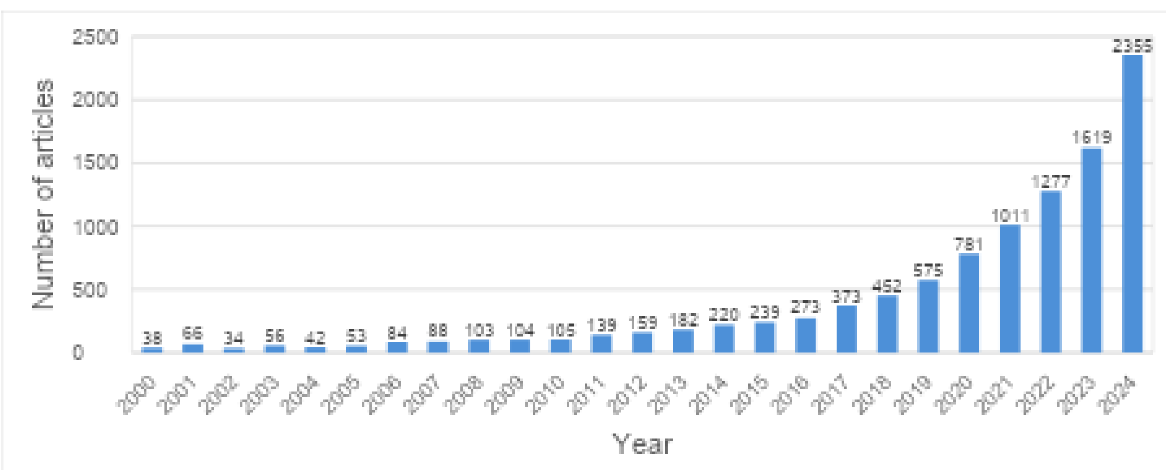
Data and methods

The data used in this study was obtained from Science Direct as a high-quality scientific database that provides access to the full text of articles that might be used in a further, deeper, more specialized analysis. As this paper considered the originality of literature, the search was conducted on publications classified as research articles.

The terms, period and formulas selected were outlined as follows. The term "environmental degradation" was selected to represent the broader concept of the negative impact of human activity on the environment, and the term "sustainability" was included to capture the balance between degradation and conservation efforts. Given that the objective of the study is to study the main methodologies used to measure environmental degradation and sustainability and used to shape economic policy, the term, "GDP", which is broadly used as proxy, was added in the search. The period of search is 2000 – 2024, this is justified following the international agenda reviewed that shows that the study of a wider conceptualization of the environment deterioration by human impact and the need for a long-term sustainability frame of work gained prominence in the early 2000's.
The operators "AND" and "OR" were employed to merge the phrases into de query. The retrieved formulas were: "TS = ("environmental degradation" AND "GDP" = (2000-2024)". The search results were exported to the Rayyan software for screening.
2.2 Output analysis

A total of 10,428 articles were collected. Figure 1 shows the articles' annual distribution from 2000 to 2024, and it can be seen and exponential growth during the last years. In 2000, just 38 articles were published, and a significant increase is observed in comparison with the 2355 publications of 2024.

Figure 1. The articles' annual distribution from 2000 to 2024



Source: Prepared by the authors based on the research carried out.

Considering the exponential growth in the number of articles and prioritizing articles that reflect the current state of knowledge and allow us to identify possible emerging trends, all articles published between 2000 and 2019 were excluded. The articles published from 2020 to 2024 account for 68% of the total which was considered a representative amount of research of the total initial period selected to identify trends. Then the 7,043 papers from this period were extracted. Of the 7043 selected articles, it was observed that 50% are concentrated in ten journals, prioritizing the most influential journals and papers all articles published in other journals were excluded.

Considering the publications between 2020 to 2024, the Top 5 journals with more related articles published are *Resources Policy* with 878 papers accounting for 12%, followed by *Journal of Cleaner Production* (714), *Journal of Environmental Management* (443), *Heliyon* (302) and *Renewable Energy* (275), together represent 40% of the articles selected. The next five journals are

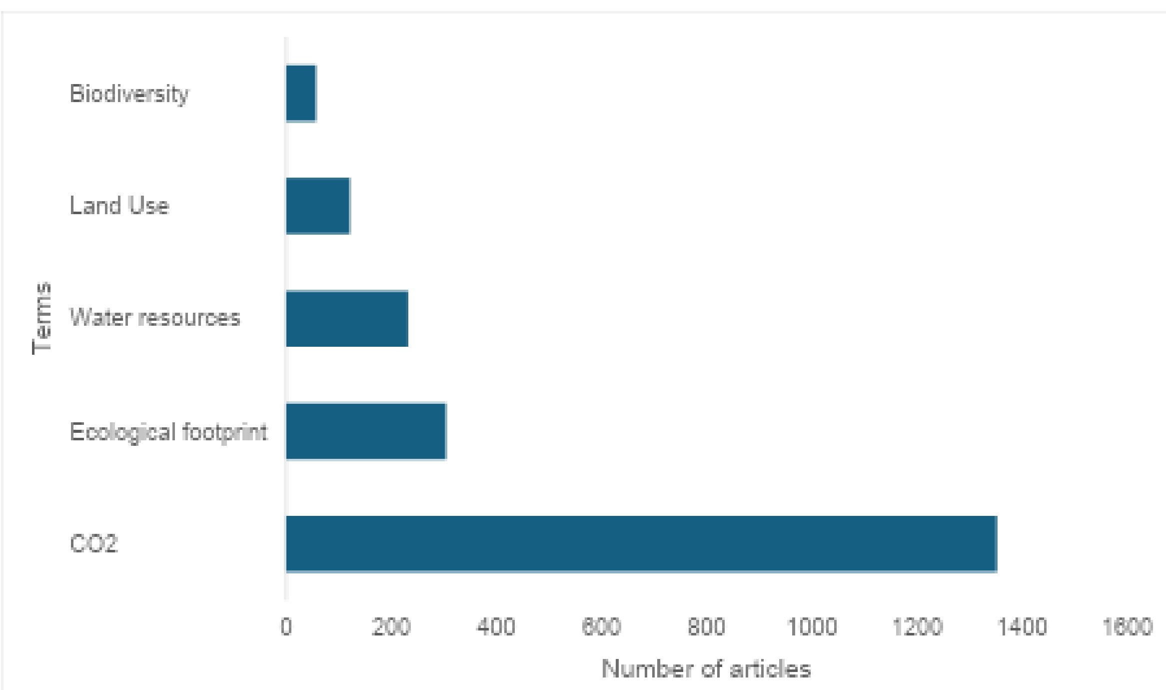
Energy Economics (217), *Ecological Indicators* (211), *Science of The Total Environment* (209), *Energy* (199) and *Technological Forecasting and Social Change* (148).

The information of the 3596 articles published in the top 10 journals was exported to the Rayyan software for title, keywords and abstract screening. After the search and eliminations of duplicates, 30 articles were excluded.

A thematic overview analysis was conducted by screening titles and abstract articles. Previous analysis was complemented by the leading frameworks (Richardson et al., 2023; Rockström et al.,2009; Steffen et al., 2015) and previous bibliometric analysis on the field (Xie et al., 2020). Specific terms for environmental degradation were identified and based on keyword occurrence and the most frequent methodologies used to approach environmental degradation and sustainability in recent economic research were classified into seven thematic clusters. First category included the use of greenhouse emissions and CO_2 emissions, the second category included ecological footprints, the third category identified were related to water resources, the fourth to land use, the fifth to biodiversity, the sixth to sustainability and the last one was reserved for other articles nonrelated to the study. The results showed that most articles used a methodology related to greenhouse gas emissions and carbon dioxide emissions, followed by the ecological footprint framework and other approaches related to the degradation of water resources, land use and biodiversity. Figure 2 shows the results from the screening of a total of 3569 articles. The results are consistent with a random sample of 10% of the articles which abstracts and keywords that were closely examined.

Figure 2.

Number of articles by environmental degradation measurements.



Source: Prepared by the authors based on the research carried out.

Most articles focus on carbon dioxide emissions, including recent studies (Alam & Hossain, 2024; Cheng et al., 2021; Ding & Zhang, 2023; Hao et al., 2021; Jaman et al., 2024; Obobisa et al., 2022; Yıldırım et al., 2022). Some studies explore the effects on both CO_2 emissions and Ecological Footprint, as a more comprehensive measure of pollution (Ha Van et al., 2024; He et al., 2024; Shen et al., 2024). Other papers only examine the Ecological Footprint as an alternative measure of environmental quality (Azimi & Rahman, 2024; Guo, 2024; Luo & Sun, 2024; Sarwar et al., 2024; Sohag et al., 2024; Yasir Mehboob et al., 2024). To a lesser extent, there is a branch of research that considers environmental degradation in terms of water pollution, land use, biodiversity loss, as well as through family footprints (Bambi & Pea-Assounga, 2024; Cheng et al., 2024; Du et al., 2024; Haubrock et al., 2024; Martínez-Guijarro et al., 2024).

The search for specific methodologies used to measure sustainability required additional attention. While conducting the screening process the term “sustainability” showed up in 921 articles. However, reviewing the abstracts we realized that most of the articles did not use a particular methodology to measure sustainability. In-deep analysis two specific indicators were identified load capacity factor (LoCF) and biocapacity explicitly included or balanced with ecological footprint. These approaches only were found in 106 articles of the sample. 50% of these articles were published in 2024, 23% in 2023 and the rest between 2020 and 2022.

The LoCF, which is based on the Ecological Footprint and Biocapacity methodology, is regarded by some researchers as a thorough indicator of environmental sustainability. This is because it considers both the demand and supply sides of the ecosystem and complements studies of other environmental degradation measurements or indices (Afshan & Yaqoob, 2023; Caglar et al., 2024; Ge & Mehmood, 2024; Hossain et al., 2023; Özkan et al., 2024).

In conclusion, even though the literature recognizes the challenge of environmental degradation and the need to focus on sustainability, this bibliometric analysis showed that researchers mostly focus on carbon dioxide emissions and related methodologies, which partially reflect the human impact on the environment. Additionally, it was found that new approaches are slowly starting to gain attention in the academic field, and that more comparative studies are needed, as is going to be discussed in the next section.

DISCUSSION

The Environmental International Agenda

Since the 1940s, international cooperation on the conservation and responsible use of natural resources has been a recurring concern on the global agenda, viewed as a potential factor affecting world peace. The issue first emerged in connection with forestry policy (Zon, 1949). Key milestones include the founding of the Food and Agriculture Organization of the United Nations (FAO) in 1945 and the United Nations' first conference on the topic—the Scientific Conference on the Conservation and Utilization of Natural Resources—in 1949. In 1950, the International Meteorological Organization was officially established, playing a key role in promoting and standardizing climate measurement and observation methods worldwide.

The United Nations Conference on the Human Environment—also known as the First Earth Summit or Stockholm Summit—was held in 1972. It marked the first major international initiative recommending global action to protect the environment (United Nations, 1972). The conference outlined principles for conserving and improving the human environment, along with a plan of action containing recommendations for international cooperation. For the first time, climate change was formally addressed, with governments urged to consider the likelihood and scale of its impacts. The establishment of monitoring stations to track long-term atmospheric changes—whether natural or human-induced—was also proposed. Additionally, the conference led to the creation of the United

Nations Environment Programme (UNEP), the Environment Fund, and the Environment Coordinating Board. Table 1 summarizes key UN environmental actions from 1949 to 2023.

Table 1.

Key environmental UN actions from 1949 to 2023.

Year	Instance	Objective or key actions
1949	United Nations Scientific Conference on the Conservation and Utilization of Resources.	Management of natural resources to benefit economic and social development (not conservation).
1950	World Meteorological Organization (WMO).	Ensure and facilitate cooperation between national meteorological services and promote and unify measuring instruments and observation methods.
1972	United Nations Scientific Conference The first Earth Summit was held in Stockholm.	Stockholm Declaration and Action Plan for the Human Environment. The most prominent issues were water resources, marine mammals, renewable energy sources, desertification, forests, the environmental legal framework, and the environment and development.
1977 – 1978	United Nations Water Conference.	The first Global Conference on Water, Focusing on Access and Sanitation Services, was held in Argentina.
1979 -1980	Governing Council of the United Nations Environment Programme (UNEP).	The first international climate instrument, the Convention on Long-Range Transboundary Air Pollution, was adopted. It expressed concern about the destruction of the ozone layer and recommended measures to limit the production and use of chlorofluorocarbons F-11 and F-12.
1988	UNEP	The Intergovernmental Panel on Climate Change (IPCC) was established. Global warming and the destruction of the ozone layer gained increasing prominence in public debate and on the international political agenda. A comprehensive review of climate change was launched, accompanied by corresponding recommendations, including possible response strategies to delay, limit, or mitigate the impact of climate change.
1992	UNEP Rio Earth Summit.	The Rio de Janeiro Declaration established a new framework to protect the integrity of the global environment and promote development. It entered into force in 1994. The most important action was to stabilize atmospheric concentrations of greenhouse gases at a level that would prevent dangerous anthropogenic interference with the climate system. Negotiations began on the United Nations Convention to Combat desertification, which entered force in 1996. The

Year	Instance	Objective or key actions
		following agreements were adopted: Agenda 21, a formal global consensus on development and environmental cooperation, and the Declaration of Forest Principles. The United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity were opened for signature as legally binding instruments.
1992	International Conference on Water and the Environment.	Derived from the Rio Earth Summit, it addresses the management and development of water resources through the impact of climate change on these resources, resource protection, quality and ecosystems, urban development, food production, and coordination mechanisms.
1997 1998	United Nations General Assembly (Earth Summit +5)	Kyoto Protocol is adopted. Its objective was to reduce total carbon dioxide and other greenhouse gas emissions from industrialized countries by at least 5% compared to 1990 levels during the commitment period from 2008 to 2012.
2000	United Nations General Assembly Millennium Summit	It established the eight Millennium Development Goals (MDGs), with one objective focused on ensuring environmental sustainability.
2002	World Summit on Sustainable Development	Held in Johannesburg, it gave rise to a new Action Plan.
2005	United Nations Framework Convention	The Kyoto Protocol entered into force seven years after negotiating with 160 countries.
2012	United Nations Conference on Sustainable Development Rio+20	Held in Rio de Janeiro, Brazil The document "The Future We Want" was published. It contains clear and practical measures for implementing sustainable development. The conference focused on two main themes: the green economy in the context of sustainable development and poverty eradication and the institutional framework for sustainable development. The result was more than 700 voluntary commitments and the creation of new partnerships to promote sustainable development.
2015	United Nations Conference on Sustainable Development	It gave rise to the 2030 Agenda and its seventeen sustainable development goals, with five objectives focused on caring for the planet.
2015	Conference of the Parties (UNFCCC) COP 21, Paris	A historic agreement was reached to combat climate change and accelerate and intensify the actions and investments needed for a sustainable, low-carbon future. It is adopted by 196 parties

Year	Instance	Objective or key actions
		and came into force in November 2016 as a legally binding instrument. Its objective is to strengthen the global response to the threat of climate change by limiting global warming to well below 2 degrees Celsius, preferably 1.5 degrees Celsius, compared to pre-industrial levels, through the submission every five years by each nation of its climate action plans or Nationally Determined Contributions (NDCs).
2018 – 2028	International Decade for Action, Water for Sustainable Development.	The goal was to accelerate efforts to address access to drinking water and sanitation, pressure on water resources and ecosystems, and the growing risk of droughts and floods.
2021	Conference of the Parties (UNFCCC) United Nations Climate Change Conference COP 26, Glasgow	A non-binding agreement signed by nearly 200 parties addresses outstanding issues pending implementation of the Paris Agreement on carbon markets and transparency. The consensus was reached on three pillars: adaptation or aid to address and manage losses for already-affected countries, mitigation or reduction of CO2 emissions, and financing for developing countries.
2023	United Nations Water Conference 2023	The Water Action Agenda was adopted, representing commitments to achieving the SDGs and their water-related targets.

Note: Authors' elaboration based on Jackson (2021) and United Nations (2021).

It was not until the early 1990s that water resource management and biodiversity began to receive greater attention, though they were still viewed as consequences of climate change rather than integral, interdependent components of the environment. Until then, efforts had focused mainly on pollution reduction, with less emphasis on responsible resource management, overexploitation, or restoration. The adoption of the Kyoto Protocol in the mid-1990s marked a turning point, targeting carbon dioxide emissions as the main driver of climate change (Jackson, 2021). Only in the early 2000s did the broader concepts of environmental sustainability and sustainable development gain prominence, along with the recognition of environmental degradation beyond air pollution. By the 2010s, discourse began to acknowledge irreversible environmental damage, the need for financial compensation to affected countries, the limited effectiveness of existing measures, and disparities in national commitments. As a result, attention shifted from merely delaying damage to actively mitigating and conserving both renewable and nonrenewable natural resources, while strengthening adaptation to increasingly probable natural disasters.

From an economic perspective, natural resources were once seen as infinite, productive assets driving human progress and improved living standards. Over time, they came to be recognized as finite, posing limits to development and even threats to existing living standards. From a sustainability viewpoint, the term natural resources—implying productive inputs—has gradually been replaced by environment as the space supporting human life, and more recently, by biosphere integrity, emphasizing the overall health of Earth's life-support systems.

The concept of the biosphere—compared to environment or natural resources—is broader and more technical, providing a foundation for comprehensive frameworks that examine the relationship between the planet and human activity. The biosphere can be understood as one of Earth's four layers and the only one that supports life. It encompasses all ecosystems, which are functional units composed of living organisms, their non-living environment, and the interactions among and between them (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, 2023). The concept is also tied to the Gaia hypothesis, which posits that the biosphere is a single, complex, self-regulating system that creates and maintains favorable conditions for life—not only human life (Lugo Hubp, 1992). Human-induced increases in the Earth's average temperature are now altering the functioning of ecosystems. Although ecosystems have historically adapted to climate change, the pace and scale of current changes primarily threaten the environmental conditions essential for human activity. Recent literature exploring Gaian and anti-Gaian feedback underscores the need for a multidisciplinary rethinking of how we understand the Earth as a complex, dynamic system (Free & Barton, 2007; Kirchner, 2002).

Closely aligned with this comprehensive perspective is the Planetary Boundaries framework (Richardson et al., 2023; Rockström et al., 2009), which addresses humanity's operational needs by defining thresholds beyond which Earth's life-support systems are at risk. It emphasizes that economic growth and human development are impossible without maintaining biosphere integrity. The framework identifies nine interrelated boundaries that represent safe global limits: (1) climate change, (2) biogeochemical flows, (3) freshwater use, (4) novel entities, (5) atmospheric aerosol loading, (6) stratospheric ozone depletion, (7) ocean acidification, (8) biosphere integrity (genetic and functional), and (9) land-system change.

Because these boundaries are interconnected, the impact of economic activity on the environment must be assessed holistically rather than focusing solely on mitigating climate change. For example, human actions can directly affect multiple boundaries: CO_2 emissions contribute to climate change and, indirectly, to ocean acidification and biodiversity loss. At the same time, activities like introducing genetically modified species can directly harm biodiversity, compounding stress on ecosystems independently of climate impacts. Similarly, freshwater resources may be depleted faster than they can be replenished and preserving them might be more immediately achievable than reducing greenhouse gas emissions. Ultimately, conserving, restoring, and enhancing ecosystems is as vital as economic and social development.

Building on the work of Steffen et al. (2015) and Rockström et al. (2009), and recognizing the interdependence of the nine planetary boundaries, it becomes clear that economic activity must be examined in relation to the full spectrum of biosphere integrity—not just individual components. For example, carbon dioxide emissions contribute to climate change, which in turn affects oceans, biodiversity, and the atmosphere. Yet human activity also directly impacts the biosphere—independent of climate change—through actions such as introducing genetically modified species, which can degrade ecosystems in other ways. It remains an urgent need to study, quantify, and monitor several planetary boundaries that are still poorly understood.

Environmental Degradation

International consensus has facilitated the development of standardized methodologies and tools for measuring environmental factors deemed relevant to human activity over time. The next section summarizes the most widely used approaches in both academic literature and policy.

Greenhouse Gases

One of the earliest methods globally studied was the measurement of greenhouse gas (GHG) emissions. This approach highlights the importance of the atmosphere, whose composition has evolved over time and currently sustains Earth's stable temperature and ecosystems. Solar radiation is partially reflected into space and partially absorbed by Earth's surface, while atmospheric gases absorb and re-emit heat, helping to regulate the planet's temperature. Some of these gases occur naturally, such as water vapor from ocean evaporation, while others result from human activity. The 1972 Stockholm Action Plan proposed establishing monitoring stations to track long-term atmospheric changes—whether natural or human-induced. These efforts were later reinforced by the 1987 Montreal Protocol, which aimed to protect the stratospheric ozone layer (Intergovernmental Panel on Climate Change [IPCC], 2022).

Over time, methodologies and country reporting requirements have been updated and refined. Greenhouse gases differ in concentration, atmospheric lifespan, and their capacity to absorb energy. As a result, monitoring expanded to include emissions from anthropogenic activities such as deforestation, land use and land-use change, livestock production, fertilization, waste management, industrial processes, and especially fossil fuel combustion. Countries were later asked to report not only emissions but also estimated absorption through natural sinks like forests and mangroves, as well as through industrial removal techniques. These developments have led to increasingly detailed emission inventories by activity and country (IPCC, 2019b).

Carbon Dioxide (CO2) or Carbon Footprint.

Carbon dioxide is recognized as the primary anthropogenic greenhouse gas, with the greatest potential to contribute to global warming, and thus serves as the main indicator in climate change assessments. As shown in the Bibliometric analysis Carbon dioxide emissions are still the most frequently used indicator to study the impact of economic activities on the environment. A significant amount of the studies from the Bibliometric analysis supported their findings on the study of the relationship between CO_2 emissions and diverse other indicators and fields, including trends like renewable energy, green energy transition, digitalization or eco-technological innovations (Chen et al., 2024; Idroes et al., 2024; Junliang et al., 2024; Kashif et al., 2024; Kilinc-Ata et al., 2025; Kilinc-Ata & Proskuryakova, 2024; Kinyar & Bothongo, 2024; Sheraz et al., 2024).

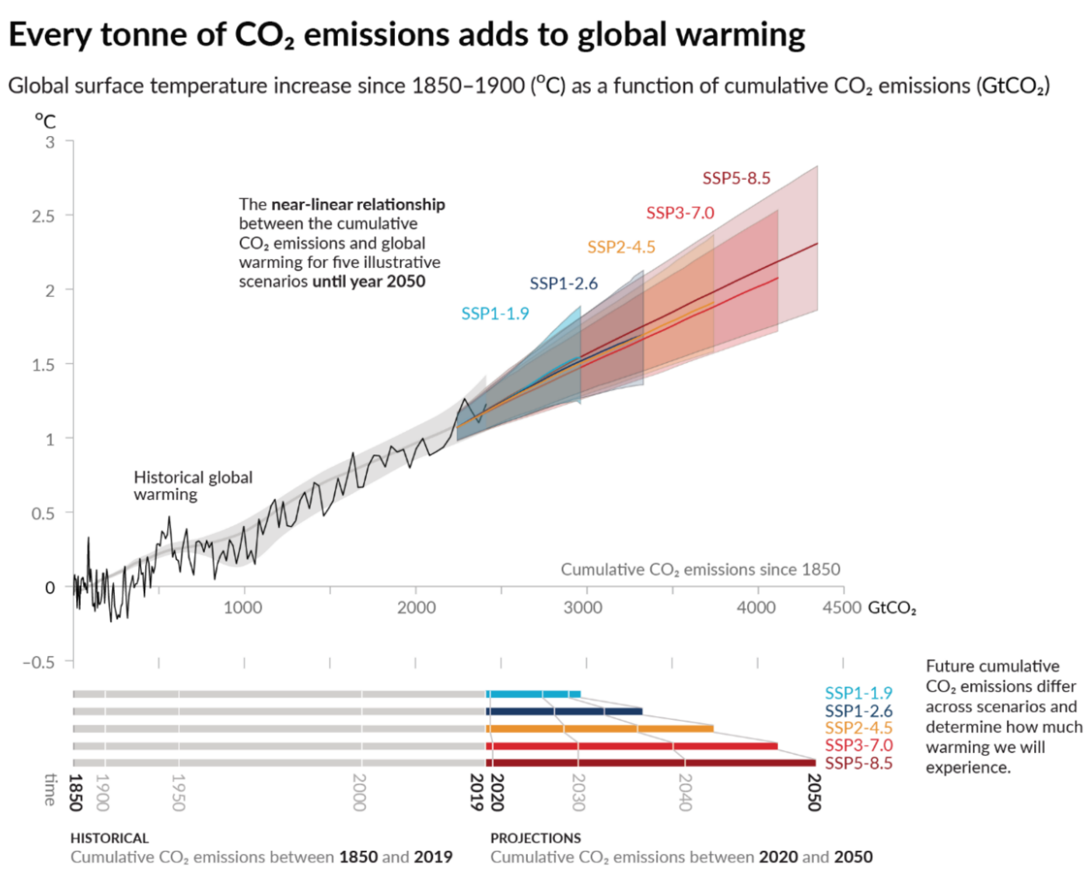
While debate persists over whether rising global temperatures are a natural part of Earth's evolution or driven by human activity, the IPCC (2023) has stated that unequivocally climate change is anthropogenic. It defines climate change as a shift in atmospheric composition directly or indirectly caused by human actions, adding to natural variability and resulting in a rise in Earth's average temperature over time.

The majority of carbon dioxide emissions stem from the combustion of fossil fuels such as oil, gas, and coal. This view holds that climate change has already produced some of the most profound impacts on the biosphere, including ocean acidification, altered weather patterns, and disruptions to the water cycle.

The IPCC (2021) outlines a series of temperature increase scenarios based on historical global warming trends since 1850 and the projections of five shared socioeconomic pathways (SSPs), which reflect global trends in factors such as education, population growth, urbanization, income levels, and income distribution. These scenarios reflect varying levels of cumulative pollutant emissions, ranging from very low (SSP1-1.9), with a projected temperature increase of 1.0 to 1.8 °C, to very high (SSP5-8.5), with an expected rise of 3.3 to 5.7 °C in global mean surface temperature (Figure 3).

Figure *3*.

Global surface temperature increases from 1850-1900 and projections to 2100 based on cumulative CO_2 emissions.

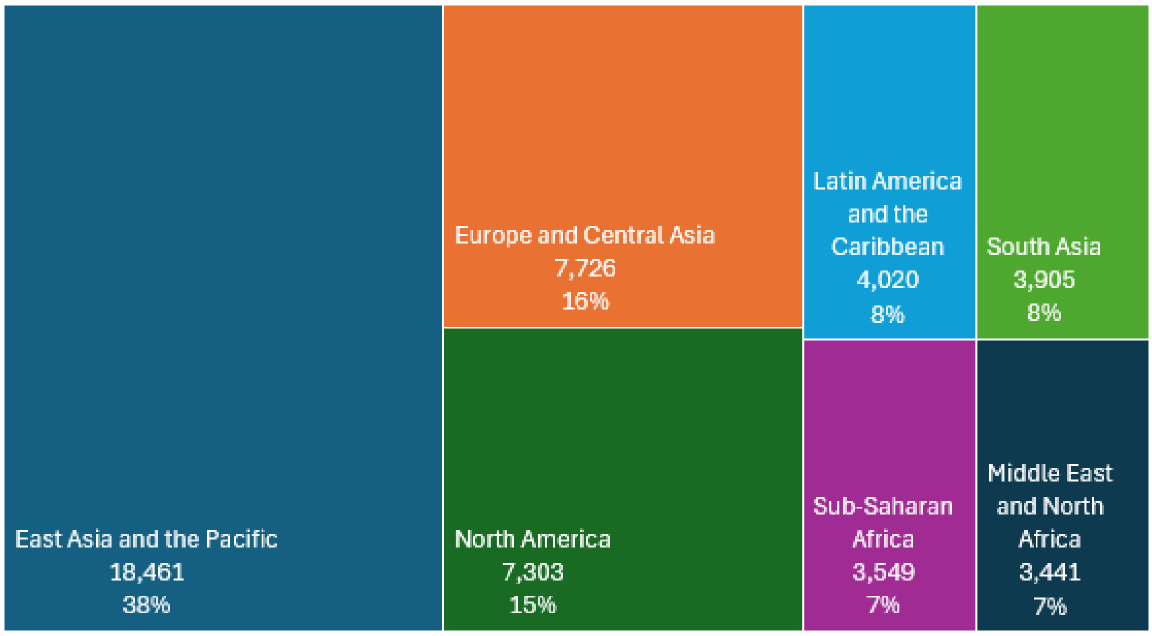


Source: IPCC (2019, 2021). Future cumulative CO2 emissions differ across scenarios and determine how much warming would be experienced.

In 2015, the international community acknowledged the urgency of limiting the global temperature increase to below 2 °C above pre-industrial levels by adopting the Paris Agreement, which has been ratified by 125 countries. Despite this commitment, there remains a high likelihood of exceeding this temperature threshold. As a result, international organizations continue to call for coordinated global action to shift shared socioeconomic conditions in ways that significantly reduce emissions—ideally aligning with the very low (SSP1-1.9) or at least the low (SSP1-2.6) emissions scenarios.

Figure 4.

World regions: global greenhouse gas emissions share, 2014 (MtCO2eq and percentages).



Source: MtCO2eq, megatons of carbon dioxide equivalent. Bárcena Ibarra et al. (2020).

Global greenhouse gas emissions contributions vary significantly by region (Figure 4): 39% East Asia and Pacific, 16% Europe and Central Asia, 15% North America, 8% Latin America and the Caribbean, 8% South Asia, 7% Sub-Saharan Africa, 7% Middle East and North Africa (Bárcena Ibarra et al. (2020). This highlights a key contradiction: regions with the highest contributions to climate change are not necessarily the most affected by its consequences. Instead, the most vulnerable regions often suffer the greatest impacts, further deepening inequality and hindering improvements in living standards. In recent years, it has become clear that national commitments are unstable, while compensation programs remain inadequate and poorly designed. International efforts have largely focused on developing alternative energy sources—particularly for industrial use—but these technologies are often privatized and financially out of reach for many economies. Moreover, this approach tends to focus solely on production-related emissions, overlooking the role of consumption patterns that drive demand.

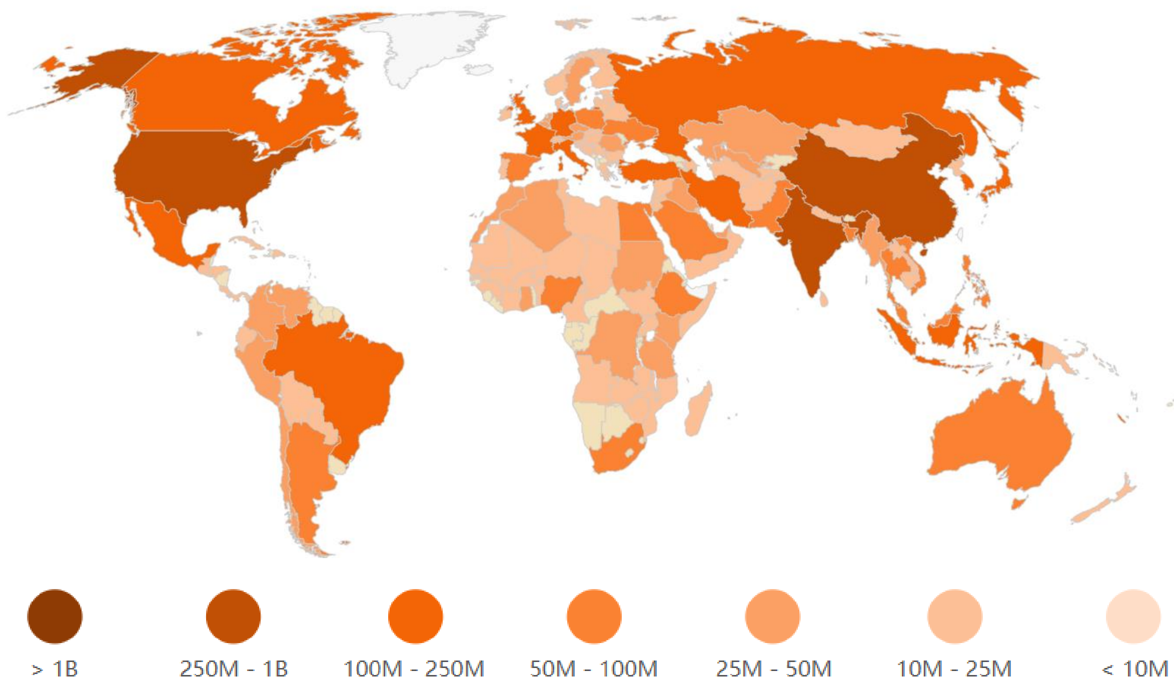
It is often assumed that mitigating climate change will lead to the self-regulation of other environmental problems. However, this perspective overlooks the time lag required for such positive effects to materialize. While interactions among different components of the biosphere are undeniable, their impacts are not immediate and may fail to address urgent local needs or prevent potentially irreversible damage.

Ecological Footprint

Another widely used methodology in the academic community is that of the Global Footprint Network, an international non-profit organization that publishes indicators on the impact of human activities on the planet's ecosystems. One of its key concepts is the ecological footprint (Figure 5), which measures the consumption and use of ecological resources and presents ecological footprint data by country (Wackernagel & Rees, 1998; Global Footprint Network, 2022).

Figure 5.

Global map of the total ecological footprint by country for 2022 in global hectares.



Source: Global Footprint Network (2022). M: Millions of global hectares. B: Billion global hectares.

This approach accounts for production pressure, defined as the biologically productive area needed by a population or product to generate the resources it consumes and to absorb emissions from fossil fuel use, based on current technology and management practices. It also incorporates international trade, recognizing that all exchanged goods embody a corresponding amount of bio productive land and sea area required for their production and waste absorption. Thus, imports are added and exports subtracted from domestic production to calculate net ecological impact. A balance is also considered in terms of traded renewable resources and ecological services (Global Footprint Network, 2022). Additionally, the framework provides estimates of Earth's regenerative capacity, which will be discussed later.

This framework shows that countries with more extractive production and consumption patterns tend to have higher ecological footprints. The publish annual data reflects both the resources used and the capacity needed to absorb resulting waste. This methodology emphasizes local management and land use, considering technologies and consumption patterns that can either reduce resource demand or enhance waste absorption. However, it does not account for non-productive ecosystems, which—despite not contributing directly to resource output—are still affected and play a vital role in the interconnected biosphere.

The Ecological Footprint indicator is commonly used in recent literature to understand the impact on the environment of human activities related to important trends as nuclear, global trade, urbanization, digital economy and Fintech or technological innovation (Ha Van et al., 2024; Kouton et al., 2024; Pata et al., 2024; Quan et al., 2024; Sarwar et al., 2024; Xiao et al., 2024; Xu et al., 2024; Yasir Mehboob et al., 2024).

Water Resources

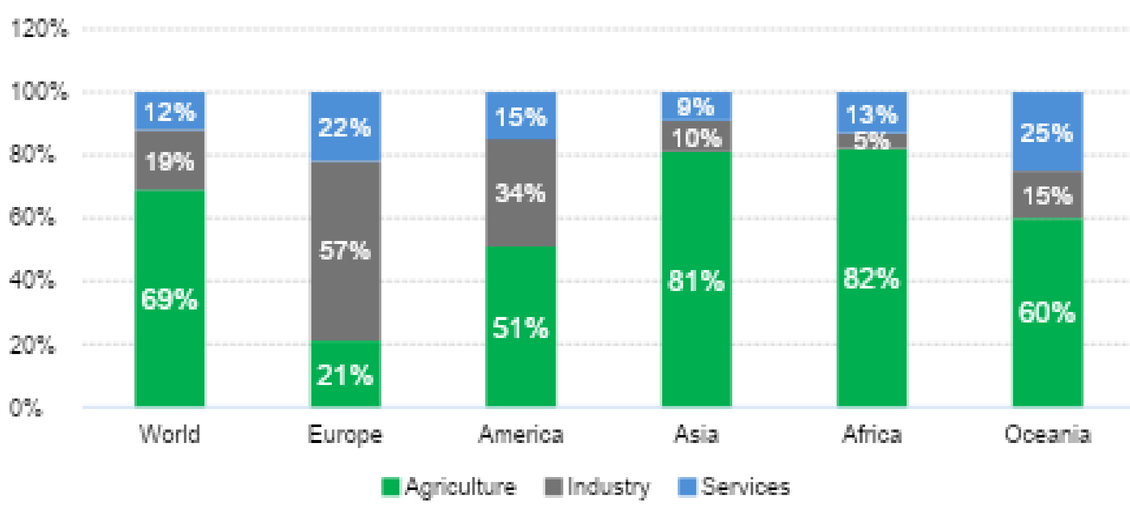
The availability and quality of renewable freshwater resources have traditionally been viewed as issues of local management, indirectly affected by climate change. However, this perspective began to shift with the first United Nations Water Conference in 2023, where water was recognized as central to the climate crisis—given that 80% of natural disasters are linked to water (United Nations Office for Disaster Risk Reduction, 2015). As seen in the Bibliometric analysis results, the inclusion of indicators that capture the state of water resources is gaining attention in literature. However, water indicators are usually not used as the main environmental degradation (Affairs et al., 2012; Martínez-Guijarro et al., 2024; Mustafa et al., 2024; Raza et al., 2024; Wang et al., 2019; L. Yang et al., 2024; Y. Yang & Cheng, 2021; Zhang et al., 2023).

The focus on water has shifted from simply expanding access and sanitation services to the urgent need to regulate its availability and affordability, promote efficient and equitable use across sectors, and ensure the conservation and restoration of aquatic ecosystems.

Water stress. The FAO's water stress indicator measures the extent to which renewable freshwater resources—mainly replenished through annual precipitation in rivers and lakes—are withdrawn for use in agriculture, industry, and services, including urban needs (Food and Agriculture Organization of the United Nations, 2018). Figure 6 shows that data analyzed using this methodology reveals that pressure on renewable water resources varies by region, though agriculture remains the most water-intensive sector in most areas (Gómez & García García, 2024).

Figure 6.

Water withdrawal percentages by region and by sector, 2020



Source: (Gómez & García García, 2024).

Water Footprint. The Ecological Footprint approach emphasizes that while countries aim to reduce water demand and increase supply, global demand patterns must also be considered. This is because production processes that satisfy local needs often occur abroad, effectively outsourcing a country's water footprint. Many countries import products made using water-intensive methods or those that contribute to water pollution, without accounting for the environmental costs (Mekonen & Hoekstra, 2011). This methodology includes three components: green water (from rainfall), blue water (from surface or groundwater that is evaporated or redirected), and gray water (the volume needed to dilute pollutants to meet quality standards). Though focused specifically on water, this framework treats water issues as part of the broader production–consumption–supply system, shifting the focus from degradation to sustainable resource use.

Ecological Footprint Family

Galli et al. (2013) later introduced the Ecological Footprint Family, which integrates the ecological, carbon, and water footprints—selected to monitor the biosphere, atmosphere, and hydrosphere, respectively. Using a multi-regional input-output (MRIO) model, this framework attributes emissions and resource use to consumption, allowing the three indicators to be analyzed together from a consumption-based perspective. Despite its comprehensive scope, the authors acknowledge the model's limitations in addressing certain environmental issues arising from human pressures. Additionally, it does not account for socioeconomic factors related to well-being, such as education, income distribution, or health. This proposal is the effort that captures more aspects of the biosphere. However, in the Bibliometric analysis we noticed that a limited number of articles have applied this or as similar family footprint (Cheng et al., 2024; Yang & Cheng, 2021).

These are not the only indicators proposed in the literature. Other suggestions include the energy footprint, biodiversity footprint, chemical footprint, and waste footprint. However, the methodologies discussed above are the most robust and standardized, enabling comparisons across countries, sectors, and periods.

Sustainability

The growing need to deepen our understanding of biosphere integrity and its relationship to human activity has become increasingly evident. It is also, important to study the emerging frameworks of sustainability as a possible course of action for strategies focus on achieving balance, breaking patterns of dependency, and promoting a long-term vision of a healthy planetary ecosystem that supports—rather than threatens—current human living standards.

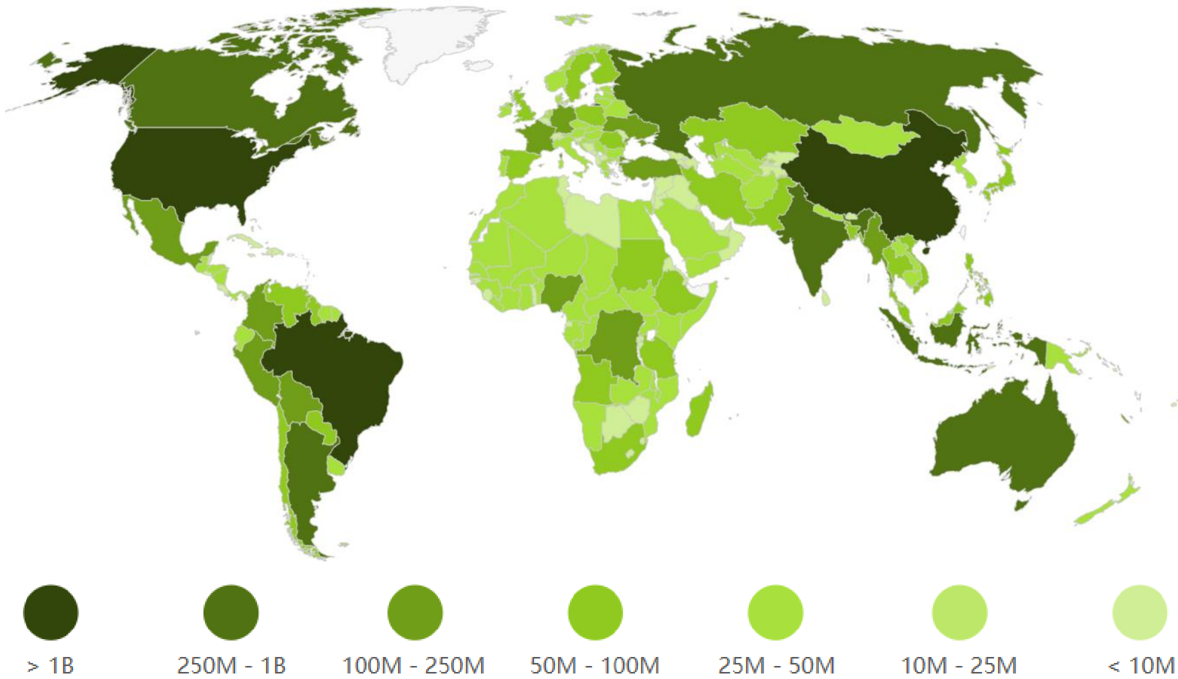
The following section presents two of the sustainability methodologies identified in the previous Bibliometric analysis the load capacity factor and the balance between the ecological footprint and the biocapacity.

Biocapacity and Ecological Footprint

The Global Footprint Network (2022) proposes the concept of biocapacity (Figure 7), which measures the productivity of ecological assets—such as cropland, grazing land, built-up areas, forests, and fishing grounds. These areas, particularly when left unharvested, also have the capacity to absorb waste, including carbon emissions from fossil fuel combustion.

Figure 7.

Map of biocapacity by country in global hectares

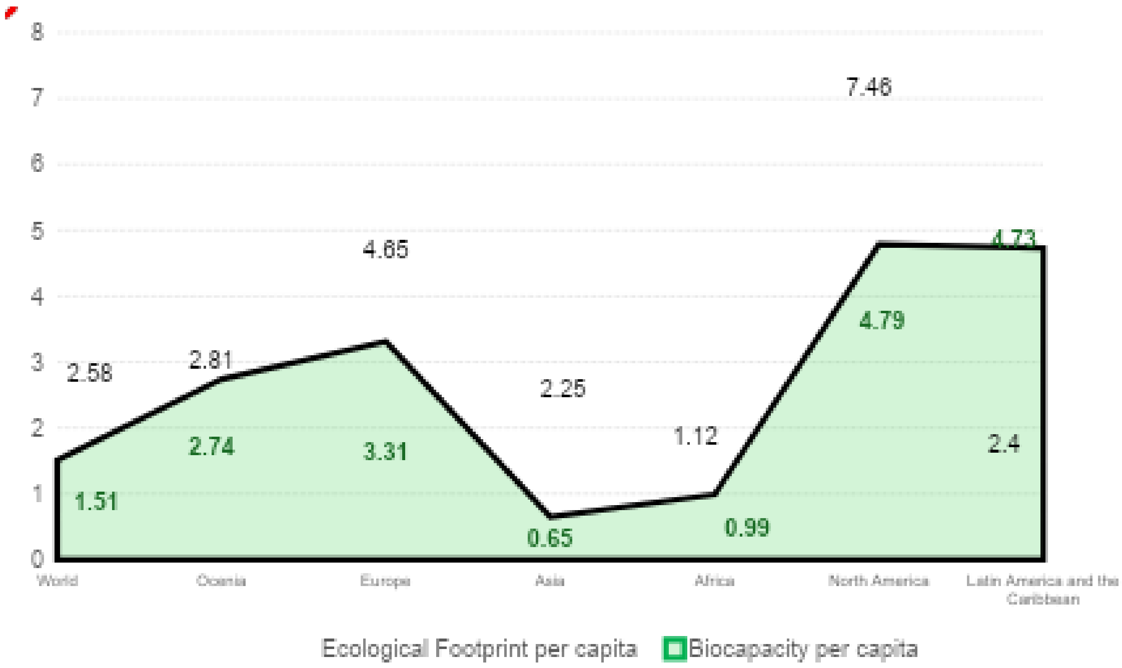


Source: Global Footprint Network (2022). M: Millions of global hectares. B: Billion global hectares.

The organization provides country-level estimates that balanced ecological footprint and biocapacity (see Figure 8). On a global scale, the ecological footprint has exceeded the planet's biocapacity since the 1970s. Regional estimates reveal that Europe has been in ecological deficit since the 1960s, followed by Asia and North America. In contrast, Latin America and the Caribbean remain the only regions that have not yet surpassed their biocapacity. Ecological Footprint indicator is frequently applied in research. However, the Bibliometric analysis revealed that only a small number of articles considered the balance between Biocapacity and Ecological Footprint or explicitly included the positive environmental aspects that capture Biocapacity. In general, it is observed that methodologies related to sustainability are not used as much as environmental degradation indicators in economic research. Notably, a growing interest in sustainability has emerged. And biocapacity has been included in recent research to capture the importance of natural resources, ecological deficits and the need for a transition towards sustainable development.

Figure 8.

Ecological footprint and biocapacity in global hectares per person, 2022.



Source: Based on information of Global Footprint Network (2022).

Load Capacity factor

This methodology builds on the work of Free & Barton (2007) and Kirchner (2002) and has been increasingly adopted in recent literature (Caglar et al., 2023; Dam et al., 2024; Dogan & Pata, 2022; Gómez & Rodríguez, 2024; Işık et al., 2024; Özbay et al., 2024; Samour et al., 2024; Uche et al., 2024; Yeboah et al., 2024; Yue et al., 2024). It proposes a more robust measure of sustainability by dividing biocapacity by ecological footprint, resulting in LoCF. This ratio indicates whether a given area or system can support its population under current development patterns. A LoCF value below one signifies unsustainability, while a value above one indicates sustainable conditions.

As summary of the discussion section two key findings emerge. First, there is no single comprehensive instrument for measuring environmental degradation, sustainability, or the overall state of the biosphere, highlighting the need for continued research and knowledge development in this area. Second, meaningful progress has been made, with international agreements and standardized tools emerging to measure specific, critical aspects—leading to the development of diverse methodologies for addressing environmental challenges.

Based on the analysis of environmental degradation and sustainability methodologies, several conclusions can be drawn. First, both greenhouse gas emissions and the carbon footprint primarily reflect the waste generated by productive economic activity. While the significance of atmospheric composition and the severe impacts of its imbalance on human living standards are well recognized, it is also clear that emission reduction efforts are deeply influenced by political cycles. As a result, national commitments have often proven unstable and insufficient to meet the global targets set by the Paris Agreement. Nevertheless, substantial progress has been made in the adoption of measurement tools and the consistent reporting of emissions by many countries. Therefore, the study of climate change and both natural and anthropogenic greenhouse gas emissions must continue—not be replaced—but complemented by broader approaches.

Second, comparing carbon dioxide emissions and their impacts at the country or regional level reveals significant discrepancies between a region's contribution to climate change and the severity of its consequences. The regions contributing the most are not necessarily the most affected, while the most vulnerable regions often bear the greatest burden (Bárcena Ibarra et al., 2020). This deepens existing inequalities and further hinders improvements in living standards. In recent years, it has become evident that national commitments remain volatile and that compensation mechanisms are inadequate and poorly designed. Moreover, while international efforts have focused on developing alternative energy sources—particularly for industrial use, these solutions are often privatized and financially inaccessible to many economies.

Third, this perspective focuses primarily on the effects of the productive sector, overlooking the role of demand patterns that drive supply. It is often assumed that addressing climate change will also resolve other environmental issues. However, this view fails to account for the time lag required for positive effects to emerge. While interactions between biospheric components are undeniable, their influence is not immediate and may fall short in addressing urgent local needs or preventing potentially irreversible damage.

Additionally, the ecological footprint has become a dominant methodological approach in literature. The efforts of the academic community in developing complementary data collection tools alongside greenhouse gas emission measurements are commendable. However, further initiatives of this kind are still needed to enhance our understanding of environmental impacts.

From this perspective, the need to transition to cleaner energy sources and production processes is increasingly clear. Equally important is the shift toward more sustainable consumption patterns. Breaking the dependence on the Earth's carrying and regeneration capacities—already overburdened in much of the world—is essential. Current methodologies emphasize local management capacity and land use, incorporating technologies and consumption habits that either reduce resource use or enhance waste absorption. They also reflect the impact of international trade by indirectly accounting for the resource pressures associated with imports and exports. However, these approaches often focus only on specific ecological assets—primarily those involved in absorbing greenhouse gas emissions—while overlooking others not directly linked to production but still essential to biosphere integrity.

Mangrove areas are an example of the importance of these other resources, which are often considered non-productive. They are considered the most efficient carbon capture and storage systems in the world, three or four times more efficient than most of the planet's forests. These coastal ecosystems, found in much of Latin America, are threatened by urbanization and tourism. They are estimated to have declined by 20% between 2011 and 2018 (Organization for Meteorology, 2021). From this perspective, the Latin American region, including the Amazon, must reduce its emissions and prioritize conserving the world's biocapacity reserves.

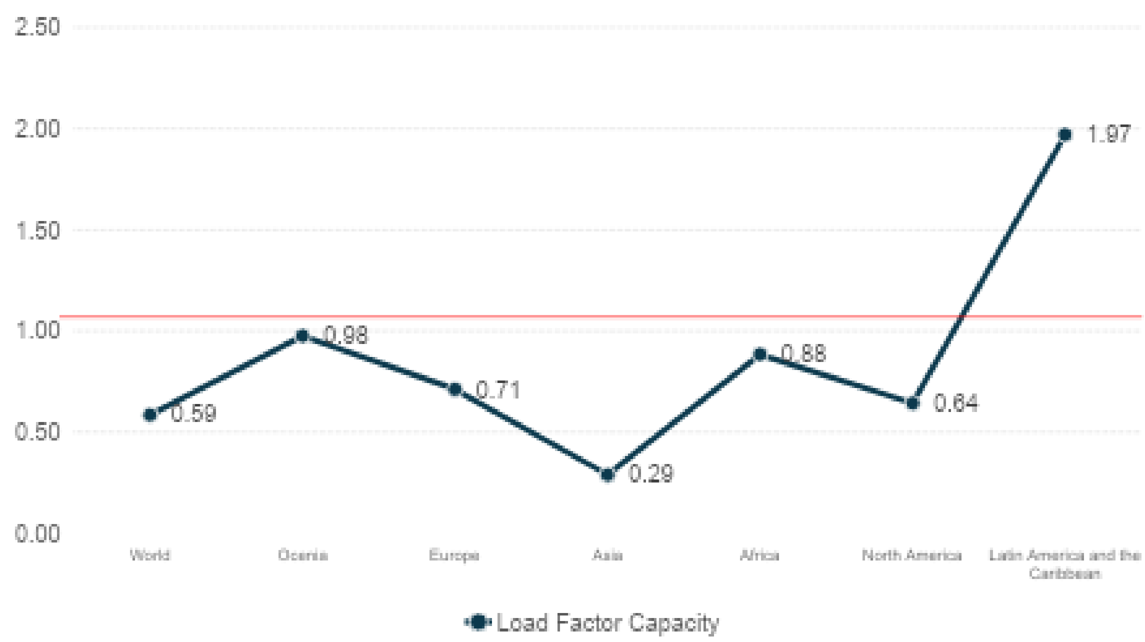
In parallel, policies focused on water resources can be analyzed. Initially, less attention is observed from the international sphere regarding this resource, which translates into less consensus in defining the problem and directing action. As mentioned above, the priority of international consumption was addressed first, expanding access to and improving sanitation services globally. Specifically, the FAO's water stress methodology focuses solely on the pressure exerted on renewable water sources, which depend on each region's changing rainfall patterns. Pressures related to water quality and the establishment of water management capacities, such as water treatment plants that prevent contaminated water from returning to natural sources, are not considered. Nor are the impacts of pressure on ocean ecosystems through desalination plants considered. In other words, the methodology only considers the primary extraction aspect due to human activity. Conversely, the water footprint methodology attempts to incorporate the capacity of groundwater or surface water sources with the necessary quality for human consumption, as well as gray water. Both methodologies focus on meeting the needs of human activity and exclude the needs of other ecosystems.

The Ecological Footprint Family proposal attempts to overcome the limitations of previous methodologies by addressing three aspects of environmental degradation. However, despite the significant effort embodied in this methodology, the authors recognize its inability to address other relevant environmental pressures generated by human activities as a limitation. Additionally, it is noted that the proposal does not consider any aspect of sustainability.

Additionally, all methodologies attempted to determine national levels of degradation and sustainability (Figure 9). However, national contributions are not directly related to, nor capable of explaining, the recorded levels of disasters. Though some proposals have considered the impact of the international trade of resources used in production or consumption, there is still no consensus. Further methodological research efforts should consider international natural and artificial resource flows across borders.

Figure 9.

Load Factor Capacity per person, 2022.



Source: Based on information of Global Footprint Network (2022).

Finally, although the methodologies focus on meeting human production and consumption needs, none address well-being as a general standard of living. In other words, they do not consider socioeconomic factors such as education, income distribution, and health.

CONCLUSIONS

This paper aims to identify and study the primary methodologies employed in research related to economic impacts during the last decades. This review aims to contribute to the generation of knowledge that allows us to understand how society can continue growth and development patterns that are in real harmony with the planet's ecosystems in the short term while creating balance in the long term. The review also seeks to provide helpful information on the limitations and shortcomings of leading methodologies.

A bibliometric analysis was conducted. Then the leading methodologies were reviewed in relation to the historic evolution of environmental perspectives in the international agenda. The leading methodologies identified are greenhouse gas and carbon dioxide emissions and ecological footprint, which are strongly related to climate change. However, other methodologies are gaining attention, and they focus on aspects of the biosphere that are not captured by climate change indicators, like water stress, water footprint or biodiversity. In addition, a more comprehensive approach is identified, ecological footprint family, that is a combination of indicators. Also, the need to measure not just degradation but include the conservationist efforts are captured by methodologies like the family footprint, which is present in the bibliometric analysis in recent years.

However, the most frequent measurements used in research remain incomplete and evolving. Existing indicators, while useful, fail to capture the full range of human effects on the biosphere. Understanding current methodologies is thus crucial to recognize their contributions and limitations, and to develop solutions that are more effective.

Theoretical contributions

This study reveals significant progress in recognizing and collecting data, as well as developing increasingly standardized and updated tools to understand this dynamic. However, it is also evident that more work is needed. It is no longer possible to properly understand environmental degradation or sustainability with a single methodology because the results are inconclusive. Non-governmental actors' efforts and contributions in generating methodological proposals are also noteworthy. These actors have the capacity to act independently of the public sphere and international agendas and are open to developing knowledge across diverse disciplines.

There has been a shift in the theoretical and applied conceptualization of the importance of biosphere integrity, moving beyond the degradation of resources necessary for human activity or the sustainability of these activities, to a planetary space whose evolution may continue even after the extinction of humanity. Some aspects of biosphere integrity are not directly related to productive processes and therefore do not attract the attention of the international community. One example is the loss of biodiversity. However, the idea that everything is a system studied disjointedly through the narrow lens of different disciplines of knowledge has been lost. Consequently, the effects on ecosystems are incomprehensible, and we are far from understanding the totality of factors influencing their interrelationship and potential impact on ecosystems and economic activity. Additionally, the effects must be considered both immediate and long-term, as well as local and global. On the one hand, there is a close relationship with national decisions that directly impact human development indicators and the control of currently used indicators of environmental degradation. However, limits are ignored because the biosphere has no political borders. This is how increasingly frequent and unpredictable natural disasters can be understood.

After reviewing different methodologies, it can be concluded that interdisciplinary research is necessary. The importance of atmospheric gas composition and its devastating, widespread effects on living standards are recognized. Therefore, the study of climate change and greenhouse gas emissions, whether natural or from human activity, must continue alongside each other. Although the ecological footprint methodology is currently dominant, it is evident that it relies on information collected from carbon dioxide emissions. In other words, the two methodologies complement each other. The latter methodology makes it clear that we must not only transition to cleaner energy sources but also change our unsustainable global consumption patterns. It is necessary to break our dependence on the carrying or regeneration capacities of natural systems, which are already overloaded in most parts of the world.

Practical contributions and future research

Clearly, factors related to biosphere integrity that are closely tied to local issues, such as water resource management, introduction of new or disappearing species, chemical pollution, and other limits posed by the Planetary Boundaries framework, are missing. This exclusion may be due to practical issues, such as a lack of information, measurements, and standardization, or it may be due to a lack of willpower.

Based on a review of leading methods of environmental degradation and sustainability, one could argue that climate patterns and international economic activities surpass political and geographical boundaries. However, policies are dictated within national borders with an incomplete understanding of human activity's pressure on the environment. Therefore, the overall findings indicate that further research is needed to develop more accurate measurement methods for environmental degradation and sustainability levels, as well as to disseminate progress to avoid misleading policymakers and hindering humanity's and the world's progress. As a result of this study, it is also necessary to be cautious.

Study limitations and future research

This paper studies the leading methodologies used in research related to economic impacts during the last decades. To advance knowledge researchers, practitioners or policy makers could benefit from applying interdisciplinary approaches, diverse data sources or other research methods. Future research could also focus on identifying sectorial, regional or specific technological innovations, and sustainable practices.

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