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REVIEW ARTICLE

Economic assessment of the ecological footprint's impact on ecosystem productivity

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Abstract: The evaluation of humanity's ecological footprint has become imperative in contemporary discourse due to escalating environmental concerns. Approaches to economically assess this footprint now employ concrete tools, such as cost–benefit analysis, input–output modeling, contingent valuation, and ecological efficiency ratios, which capture both direct and indirect impacts on ecosystems. This study provides an overview of these prevailing approaches in economic evaluation, emphasizing their methodological application and their significance in quantifying the ecological consequences of human activities. Particular attention is given to the valuation of ecosystem services, including measurable processes, such as oxygen production, carbon sequestration rates, water purification efficiency, and biodiversity indices, which are critical for a comprehensive assessment of humanity's ecological footprint. The article also examines assessment frameworks through legislative and policy instruments, highlighting the role of environmental impact assessment, the United Nations Sustainable Development Goals, and international agreements, such as the Kyoto Protocol and the Paris Agreement. The analysis evaluates the adequacy of these measures and identifies areas where legislative improvements are required, particularly in climate action, technological innovation, water resource management, sustainable production, and biodiversity conservation. This paper integrates scientific perspectives from seminal scholars. It applies empirical data on the ecological and economic role of forests, focusing on carbon storage potential, biodiversity preservation metrics, soil and water protection functions, and modeling impacts of air quality improvement. The study concludes by underscoring the need for legislative enhancements and the adoption of open data practices at both national and international levels to comprehensively address and mitigate the ecological footprint. Overall, this article combines economic valuation techniques, quantitative indicators, and policy analysis to provide a scientifically rigorous perspective on evaluating and reducing the ecological footprint to support sustainable development.

Keywords: Ecological footprint; Carbon dioxide emissions; Economic evaluation; Ecosystems

1. Introduction

Human activities leave a substantial ecological footprint on the planet, affecting ecosystems, biodiversity, and natural resources. Evaluating this impact through an economic lens has gained traction to comprehend the real costs and benefits associated with various human endeavors. Several approaches have emerged, offering diverse perspectives on how to assess and address the ecological footprint from an economic standpoint.

In recent years, the economic perspective on biodiversity and natural capital has gained prominence. As highlighted by Dasgupta,[1] natural capital—the stock of ecosystems and biodiversity—forms the foundation for economic prosperity and human well-being. The evaluation of ecosystem services is therefore not only a matter of ecological concern but also a critical economic imperative. Integrating natural capital into economic decision-making helps quantify the real costs of biodiversity loss, resource depletion, and ecosystem degradation, thereby providing a rigorous basis for sustainable development policies.[2]

The ecological footprint on ecosystem productivity is a crucial topic in today's world. Assessing the economic consequences of natural processes and human activities on ecosystems is vital for understanding and managing natural resources. Ecosystems provide a range of essential services, such as air and water purification, plant pollination, soil fertility maintenance, climate regulation, and biodiversity preservation. However, human activities, including industrialization, mass production, pollution, and deforestation, can cause a significant impact on these ecosystems.

The economic evaluation of the ecological footprint on ecosystem productivity involves several aspects. First, it includes considering the value of natural resources provided by ecosystems, for instance, assessing the value of air or water purification by ecosystems compared to the cost of artificial purification systems. The second aspect is accounting for the value of biodiversity loss and the services of nature. Every lost species or disruption in ecosystem services potentially incurs costs for humanity in the future.

Assessing the ecological footprint also involves understanding the interaction between the economy and ecology. For example, the impact of environmental factors on economic productivity, such as the influence of pollution on public health and healthcare expenses, should be considered. Having effective mechanisms for evaluating the ecological footprint enables informed decisions regarding natural resource management and development, balancing ecological and economic interests. Research in the field of economic evaluation of the ecological footprint on ecosystem productivity plays a crucial role in shaping policies and decision-making aimed at conserving nature and fostering sustainable development.

Overall, understanding the economic impact on ecosystems and evaluating their productivity are crucial aspects in developing rational strategies for conserving natural resources and ensuring the sustainable development of society.

This study aims to investigate the impact of human activities on ecosystems. The scope of this study is to analyze the interrelationship between ecosystems, natural resources, and the economic systems they support. The primary objective is to assess and quantify the economic impact of human activities on the productivity of forest ecosystems, evaluating how human economic activities affect the productivity of ecosystems. The expected outcomes of this study are specific achievements, which include assessing the monetary value of ecosystem services, identifying the most affected ecosystems, proposing sustainable management strategies, understanding the correlation between economic activities and ecological changes, quantifying the economic value of ecosystem services, and proposing measures for sustainable resource management.

Ecosystems provide a myriad of invaluable services that sustain life on Earth. From oxygen production to water purification, these services are fundamental yet often undervalued in economic assessments. The economic evaluation of these services becomes imperative in understanding the holistic impact of human actions on the environment.

2. Methods to assess the ecological footprint on ecosystem productivity

This study employed a combination of general and specialized methods to assess the economic impact of human activities on forest ecosystems and biodiversity. The methodological framework integrates ecological, economic, and computational approaches to provide a robust and comprehensive analysis.

2.1. Literature review

An extensive review of existing literature, scientific articles, and reports on ecosystem productivity, ecological footprints, and economic evaluations was conducted. This helps in understanding previous methodologies, identifying gaps, and establishing a foundation for this study.

2.2. Data collection

Utilizing diverse sources, such as satellite imagery, government reports, scientific databases, and economic surveys, relevant data concerning ecosystems, economic activities, and ecological footprints were gathered. This involved acquiring information on biodiversity, land use, pollution levels, and economic indicators.

2.3. Economic valuation techniques

Several economic valuation methods were employed to assess the impact of human activities on ecosystems, including contingent valuation, hedonic pricing, and cost–benefit analysis (CBA) to assign monetary values to ecosystem services.

2.4. Ecological assessment

To evaluate the ecological changes within selected ecosystems affected by human activities, the data on biodiversity loss, habitat degradation, and pollution levels from field surveys, remote sensing data, and ecological modeling techniques were analyzed.

2.5. Integration and analysis

To evaluate the interconnectedness of economic and ecological data, these data were integrated into our analyses. The correlations between economic indicators (such as gross domestic product [GDP] and industrial output) and ecological parameters were analyzed to understand how economic activities influence ecosystem productivity.

2.6. Advanced modeling approaches

To enhance scientific rigor, modern computational methods were incorporated. Hydrological modeling using a cascaded adaptive neuro-fuzzy inference system was employed to study rainfall–runoff relationships, providing insights into the impact of precipitation patterns on forest ecosystem dynamics.[3] This illustrates the application of computational intelligence in ecological research and allows scenario-based predictions of ecosystem responses to environmental and anthropogenic changes. In addition, ecological modeling and scenario planning were used to simulate potential future changes in forest ecosystems under varying economic and conservation scenarios.

2.7. Scenario planning and modeling

Several scenarios were developed to simulate potential future changes in economic activities and their corresponding impacts on ecosystems. Modeling techniques were utilized to forecast various scenarios and assess their ecological and economic implications.

2.8. Policy recommendations

Based on the findings, policy recommendations and management strategies were formulated, aiming to achieve sustainable economic development while preserving and enhancing ecosystem productivity.

2.9. Peer review and validation

The findings and methodologies were validated through peer review, discussions with experts in the field, and the methodology was revised based on the feedback obtained.

2.10. Documentation and reporting

The entire research process, including methodologies, data sources, analysis techniques, and findings, was documented. A comprehensive report outlining the research methodology, results, conclusions, and recommendations for stakeholders and the scientific community was then prepared.

To assess the ecological footprint on forest ecosystems and biodiversity, several effective research methods were employed in this study.

2.10.1. Socialeconomic research

This method evaluated the impact of local communities on ecosystems, the economic dependence of local communities on forest resources, and the degree of public involvement in forest conservation. Sociological research and economic indicator analysis were applied to elucidate the impact of society on forest ecosystems.

2.10.2. Forest inventory and monitoring method

This method involved measuring the territory of forest areas, determining forest stand structure, plant and animal species diversity, tree age structure, and the forest ecosystem's overall condition. Through conducting field research and utilizing data from remote sources (satellite imagery and airplanes), forest inventory and monitoring were conducted to track changes in their structure and biodiversity.

2.10.3. Assessment of the economic value of forest ecosystems

This method determined the economic value of services provided by forests, such as air purification, soil preservation, and biodiversity support. Economic models, such as contingent valuation methods or market-based approaches, were used to determine the monetary value of benefits provided by forest ecosystems.

2.10.4. Genetic research and molecular ecology

This method was employed to study the genetic diversity of species and their interactions in forest ecosystems. Genetic techniques and molecular ecology were employed to study the gene pool of species and their interactions within forests.

2.10.5. Ecological modeling and scenario planning

Using computer models to forecast potential scenarios of changes in forest ecosystems under different human activity scenarios, the models enabled the prediction of possible consequences of changes in forest usage or conservation measures.

The combination of these methods enabled a comprehensive assessment of the impact of economic activities on forest ecosystems and biodiversity, providing a complete understanding of this issue. The economic methods were also employed for assessing the ecological footprint on nature.

2.10.6. Statistical analysis methods

Statistical analyses were conducted to evaluate the ecological footprint using economic indicators, including GDP, employment, and healthcare expenses. The impact of the ecological factors on the economy was measured using correlation and regression analyses.

2.10.7. Market-based methods

These methods defined the ecological footprint based on market mechanisms. For instance, trading quota systems were used when determining the cost of air pollution. The value of ecological damage was assessed by comparing it against the market prices of equivalent goods or services.

2.10.8. Internal market methods

The value of natural resources that were not included in market transactions was evaluated. For example, biodiversity loss due to the loss of ecosystem services was assessed. These methods assessed the "unseen" values of natural resources to include them in economic calculations.

2.10.9. Contingent valuation methods

These methods evaluated the impact of people's willingness to pay for conserving nature or avoiding ecological damage. Experiments were conducted to determine the monetary value that a society is willing to pay for certain natural goods.

These economic methods contributed to a comprehensive understanding of the ecological impact of human activity on nature and enabled the consideration of this impact in making economic decisions. Several formulas were employed in this study to determine the carbon footprint (Equation 1), ecological efficiency ratio (Equation 2), and resource expenditure per production unit (Equation 3).

$$Carbon\ footprint = Fueld\ quantity \times Emission\ coefficient \quad (1)$$

$$Ecological\ efficiency\ ratio = \frac{Benefit\ or\ gain}{Ecological\ footprint} \quad (2)$$

$$Resource\ expenditure\ per\ unit\ of\ production = \frac{Total\ resource\ expenditure}{Amount\ of\ produced\ goods} \quad (3)$$

These formulas provided a basis for quantifying and evaluating various aspects of the ecological impact resulting from different activities or processes. The integration of traditional economic and ecological assessment methods with advanced computational modeling ensured a comprehensive and scientifically robust evaluation of the ecological footprint on forest ecosystems and biodiversity.

3. Literature review

Numerous researchers contributed their unique approaches to the economic evaluation of the ecological impact, expanding and deepening our understanding of the importance of preserving natural resources and ecological balance in the modern world. For example, Daly[4] is a proponent of the need for a paradigm shift in economic growth. He advocates for an economic model that operates within ecological limits and emphasizes the importance of considering these limits in shaping sustainable development. Daly's view revolves around the concept that the economy should prioritize long-term sustainability over short-term gains, acknowledging and respecting the environmental constraints imposed by nature. He advocates for the idea of sustainable development and believes that the economy should operate within ecological limits. He argues that the economy should contribute to the long-term preservation of natural resources and ecosystems.

Stern[5] focuses on the economic aspects of climate change. In his work, he emphasizes the potential economic impacts of climate change on a global scale. Stern provides recommendations on mitigating these impacts through economically rational measures and policy interventions. His approach involves evaluating the costs and benefits of actions to address climate change, suggesting that investing in climate change mitigation could be more cost-effective than dealing with its consequences. Known for his work in climate change economics, researchers believe that adverse ecological changes can be avoided through proper economic assessment of costs and benefits arising from emissions reduction measures.

Costanza *et al.*[6] assess the economic value of ecosystem services. Their work aims to quantify the value of these services and their contributions to the global economy. Their perspective underscores the significance of recognizing and incorporating the economic value of nature's services into economic assessments and policy-making processes. They actively investigate economic approaches to assess the services of ecosystems. Their work aims to evaluate the real value of natural resources that are not accounted for in traditional market assessments.

Raworth[7] presents the concept of "donut economy," which emphasizes the need for an economic system that operates within social and ecological boundaries. She advocates for an economic model that ensures both social equity and environmental sustainability. Raworth's approach suggests a balanced economic framework that considers the planet's environmental constraints while meeting society's needs. She proposes the concept of a "donut economy" based on the idea that the economy should operate within the social boundary and ecological ceiling. She emphasizes that the economy should serve to achieve social equity and preserve ecological integrity.

Several other studies have been conducted to investigate forest ecosystem services. The study conducted by Pan *et al.*[8] confirms the significant impact of forests as carbon sinks, aiding in reducing greenhouse gas emissions into the atmosphere. Pimm *et al.*[9] explore species diversity and its importance in preserving ecosystems and preventing species extinction. Nave *et al.*[10] investigate the impact of increased nitrogen inputs on carbon storage in northern hemisphere forest soils. Nowak *et al.*[11] conducted modeling on air purification by trees in the United States of America (USA) cities and their impact on public health.

The Millennium Ecosystem Assessment[12] examines the interrelationship between ecosystems and human well-being, emphasizing the importance of ecosystem services in supporting society. Collectively, these studies offer a significant contribution to understanding various aspects of ecology and the impact of ecosystems on human society. These studies also contribute valuable insights into how economics can address environmental challenges and integrate ecological considerations into economic frameworks.

4. Evaluation of the ecological footprint on ecosystem productivity

In modern societies, the need for artificial purification systems has grown significantly due to the increasing pressures of industrialization, urbanization, and intensive agriculture on natural ecosystems. While forests, wetlands, and aquatic ecosystems play an irreplaceable role in purifying air and water through natural processes, the scale and intensity of anthropogenic impacts often exceed the regenerative capacity of these ecosystems. Consequently, technological solutions have become indispensable in ensuring environmental and public health. Artificial purification systems, such as advanced filtration units, membrane-based technologies, sorption materials, catalytic filters, and advanced oxidation processes, are designed to remove pollutants and restore air and water quality where natural mechanisms alone are insufficient. For example, filtration systems are widely applied in both municipal and industrial contexts to eliminate particulate matter and toxic compounds from wastewater and exhaust gases. Membrane technologies, including nanofiltration and reverse osmosis, have become central in desalination plants and in the production of safe drinking water in regions facing freshwater scarcity. Sorption-based systems, relying on activated carbon, zeolites, or advanced nanomaterials, are frequently employed to capture heavy metals, volatile organic compounds, and emerging contaminants that pose risks to human health. Recent scientific studies have highlighted the efficiency and innovation of these methods: novel catalytic membranes and hybrid nanostructured sorbents have been shown to achieve unprecedented levels of purification, offering practical solutions to the growing environmental challenges of the 21st century.[13] However, despite their effectiveness, artificial purification systems are associated with considerable economic and ecological costs.[14] They often require high energy inputs, advanced infrastructure, and continuous maintenance, while generating secondary waste streams that need to be managed. This creates additional financial burdens on municipalities, industries, and households. In contrast, natural ecosystems provide purification services at a lower cost, relying on ecological processes that have evolved over millennia.[15]

Therefore, the integration of artificial systems should not be seen as a substitute but as a complementary measure to ecosystem-based purification. A balanced approach that combines technological innovations with ecosystem conservation strategies provides the most sustainable path forward. This perspective underscores the importance of valuing natural purification services within economic assessments, while also recognizing the need for artificial systems in safeguarding human well-being under conditions of escalating environmental pressures.

Several regulatory frameworks and legislative acts exist worldwide concerning the assessment of the ecological footprint, including:

(i) Environmental impact assessment (EIA): Implemented in various forms globally, EIAs are regulatory tools assessing the potential environmental consequences of proposed projects or developments before they are carried out.
(ii) Sustainable development goals (SDGs): Developed by the United Nations, these 17 global goals aim to address social, economic, and environmental challenges. SDGs serve as a framework guiding countries to evaluate and improve their environmental impact.
(iii) Kyoto protocol: An international treaty under the United Nations Framework Convention on Climate Change (UNFCCC) that sets binding obligations on industrialized nations to reduce greenhouse gas emissions and encourages the use of mechanisms such as carbon trading.
(iv) Paris agreement: A landmark international treaty under the UNFCCC aimed at limiting global warming to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C.
(v) National Environmental Policy Act (NEPA): Implemented in several countries, including the USA, NEPA requires federal agencies to assess the environmental effects of their proposed actions and consider alternatives to minimize adverse environmental impacts.

These regulatory acts and international agreements play a crucial role in shaping environmental policies, guiding assessments, and influencing measures taken to evaluate and mitigate the global ecological footprint.

These legislative acts reflect the importance of assessing and managing the ecological footprint. However, several aspects might require additional legislative actions or improvements, including:

(i) Climate change: There is a need to strengthen acts and international agreements aimed at reducing greenhouse gas emissions and adapting to climate change.
(ii) Development of green technologies: Enhancing legislation that promotes the development and implementation of eco-friendly technologies, energy efficiency, and the use of renewable energy sources is required.
(iii) Water resource management: It is necessary to improve acts aimed at protecting water ecosystems, reducing water body pollution, and conserving water resources.
(iv) Encouraging sustainable production and consumption: Legislative measures are required to reduce production waste, support the use of secondary materials, and increase consumer environmental awareness.
(v) Biodiversity conservation: The measures to protect vulnerable ecosystems and species should be strengthened, and stricter regulations in forestry and marine conservation laws should also be established.
(vi) Regulating these aspects may require enhancements or further development of legislative acts at both the national and international levels.
(vii) CBA: This remains a fundamental approach, quantifying the costs and benefits of human actions on the environment. It assesses various scenarios, weighing economic gains against environmental costs to determine the most favorable course of action. While criticized for oversimplification and value assignment, CBA provides a structured framework for decision-making.
(viii) Natural capital and ecosystem services valuation: This approach focuses on evaluating ecosystems' services and natural capital. It attempts to assign economic value to nature's contributions, such as water purification, soil fertility, and pollination, highlighting their economic significance. By monetizing these services, it aims to integrate environmental considerations into economic decision-making.
(ix) Input–output analysis: This is a method to analyze the interconnectedness between sectors of the economy and their environmental impact. By tracing resource use and emissions across industries,

this approach quantifies the environmental repercussions of economic activities. It provides insights into how changes in one sector affect others and the environment as a whole.

(x) Shadow pricing and market mechanisms: Shadow pricing involves assigning monetary values to environmental goods and services not traded in markets. Market mechanisms, such as carbon pricing and payment for ecosystem services, attempt to internalize environmental costs into market transactions, encouraging sustainable practices by reflecting environmental values in prices.

In this study, the main instruments utilized to assess the ecological footprint of various countries in relation to GDP have been analyzed and summarized (Table 1).

Table 1 provides an overview of various countries' approaches to evaluating the ecological footprint in terms of their GDP or specific numeric values. Germany demonstrates a substantial commitment to assessing its environmental impact by allocating approximately 8% of its GDP toward expenditure on ecological damage. This indicates a significant financial dedication to addressing environmental concerns. China follows suit, dedicating an estimated 3–5% of its GDP to cover the costs associated with ecological damage. This represents a considerable portion of its economic output directed toward managing environmental repercussions. In comparison, the USA and the Netherlands allocate 2–4% and 5–7% of their GDP, respectively, to environmental costs.[22] These figures signify notable financial commitments made by these countries to account for and potentially mitigate their ecological footprint. Brazil, with a focus on valuing ecosystem services, allocates a substantial share of its GDP (6–8%) to recognize the economic importance of its natural resources, particularly its diverse ecosystems.[23]

The data suggest that the collective expenditure on addressing the ecological footprint ranges between 4% and 8% of the world's GDP, according to broader global estimates. This emphasizes the importance of recognizing and managing environmental impacts on a global scale. Overall, the data reflect varying levels of financial commitment among different countries toward managing their ecological footprint, highlighting the substantial economic resources allocated to addressing environmental concerns.[24]

In 2022, the European Union's (EU) GDP amounted to approximately €15.9 trillion (Figure 1). GDP is an important indicator of a country's economic strength, representing the total value of all goods and services produced in a given year. The EU comprises 27 member states with developed economies, including several of the largest economies worldwide. Since its establishment in 1993, the Union has had a significant positive effect. However, in its early years, the EU faced financial crises that had to be overcome collectively. Most European countries experienced the impact of the 2008 global financial crisis, followed by the Eurozone crisis, which had a serious and lasting impact on the overall European economy.[23] During the crisis, banks closed and living standards declined, particularly around 2009, which led to widespread doubts and uncertainty about the future of many European families and consumers. As the global economic situation gradually improved, consumer outlook across Europe also recovered.

Table 1. The assessment of the ecological footprint by country in relation to GDP

Country	Type of ecological footprint	Share of GDP (%)
Germany	Expenditure on ecological damage	8
China	Cost of environmental expenses	3–5
United States of America	Cost of environmental expenses	2–4
Netherlands	Costs for ecological damage	5–7
Brazil	Value of ecosystem services	6–8
Global	Total expenditure on ecological footprint or global estimates	4–8

Abbreviation: GDP: Gross domestic product.
Data source: Author's work based on previous studies.[6,15-22]

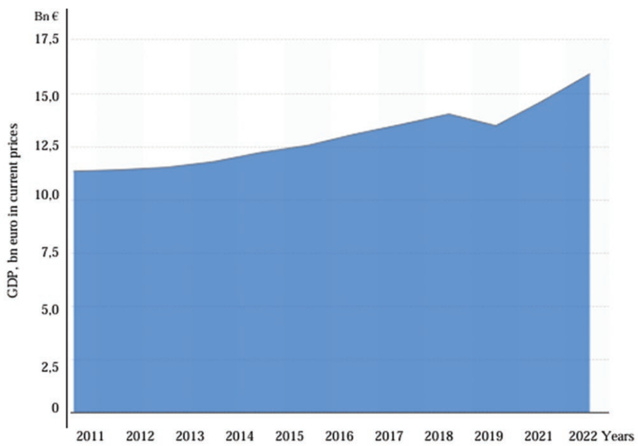

Figure 1. Dynamics of gross domestic product of the European Union from 2011 to 2022 (in bn euro at current prices). Data source[23,24,27-29]

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There remains a need to stimulate the economy, to use natural resources efficiently, and to reduce the ecological footprint on nature, which in practice often requires borrowing and increased public spending. As a result, the national debt rose sharply. It was also necessary for more economically successful countries to provide financial assistance to those in crisis, such as Greece. These experiences underscore the need for new approaches to utilizing natural resources more sustainably.[25]

While the results section compares ecological costs across countries, the analysis would benefit from deeper interpretative insights that go beyond numerical comparisons. In particular, when discussing the valuation of ecosystem services, it is important to emphasize the role of advanced computational tools in enhancing both accuracy and transparency in environmental assessments. Recent research in agriculture demonstrates the potential of explainable machine learning approaches for nutrient prediction, providing interpretable models that support decision-making at both farm and policy levels.[14] Referencing such applications illustrates how artificial intelligence (AI) can be employed across sectors, not only to optimize agricultural productivity but also to strengthen the credibility of ecosystem service valuation. By incorporating explainable AI methods, ecological and economic analyses offer enhanced interpretability, allowing stakeholders to understand the drivers of environmental outcomes and to adopt more sustainable practices. This cross-sector perspective underscores the need to integrate modern computational approaches into ecological footprint assessments, ensuring that results are both scientifically rigorous and practically actionable.[26]

From a broader interpretative perspective, the evaluation of ecological footprints across nations also reflects differences in methodology and policy integration. Germany has institutionalized environmental economic accounting, embedding ecological data directly into national accounts. China emphasizes ecosystem service valuation as part of its strategy to address large-scale environmental degradation. The United States relies on models developed by the Environmental Protection Agency, which emphasize ecosystem services and environmental liabilities. The Netherlands incorporates economic assessments into national strategies, whereas Brazil prioritizes the valuation of ecosystem services provided by the Amazon rainforest. These methodological variations, presented alongside the numerical data in Table 1, highlight the diverse ways in which countries operationalize the economic dimensions of environmental policy.

Forest ecosystems play a pivotal role in mitigating the ecological footprint through various mechanisms, including:

(i) Carbon sequestration: Forests act as significant carbon sinks, absorbing carbon dioxide from the atmosphere during photosynthesis and storing it in trees and soil. This process helps mitigate climate change by reducing the amount of greenhouse gases in the atmosphere.

(ii) Biodiversity preservation: Forests support rich biodiversity, hosting diverse species of plants, animals, and microorganisms. This biodiversity ensures ecosystem resilience and adaptation to environmental changes, thereby maintaining ecological balance.

(iii) Soil and water conservation: Forests help prevent soil erosion by holding soil particles in place with their roots, preserving soil quality and fertility. In addition, they regulate water flow, reduce runoff, and contribute to groundwater recharge, thereby maintaining water quality and availability.

(iv) Air quality improvement: Trees and vegetation in forests contribute to cleaner air by filtering pollutants and particulate matter. They absorb various air pollutants, improving air quality and human health in surrounding areas.

(v) Ecosystem services provision: Forests offer essential ecosystem services, such as oxygen production, regulation of local climate, and provision of habitat for wildlife. These services contribute to human well-being, supporting livelihoods and providing resources for various industries.

In summary, forests play a crucial role in softening the ecological footprint by sequestering carbon, preserving biodiversity, conserving soil and water, improving air quality, and providing essential ecosystem services. Protecting and sustainably managing forests are vital steps toward mitigating the environmental impact of human activities.

The largest tropical forest in the world is considered to be the Amazon rainforest, which is 3 times larger in primary forest area compared to the Congo rainforest (Figure 2). In addition, the Amazon forests have twice the area of tree cover. It is an indisputable fact that more than half of the entire area of primary tropical forests on the planet is concentrated in the Amazon. Primary forest refers to the area of forest that remains largely undisturbed by human activity. In contrast, total tree cover represents both primary and secondary forests,

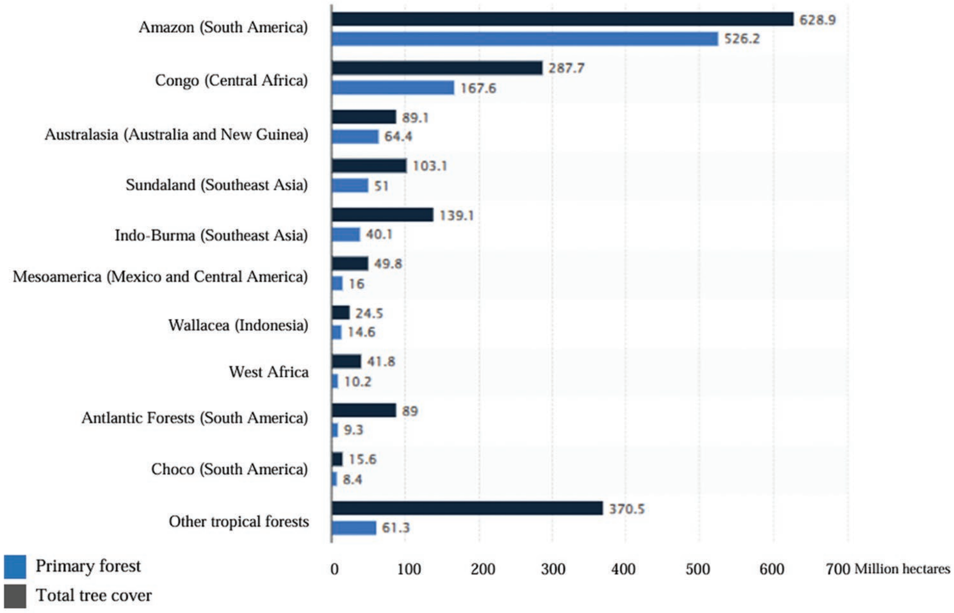

Figure 2. Primary forest extent and tree cover extent of the world's major rainforest regions in 2020 (in million hectares). Data sources[18,19]

including areas used for commercial purposes, such as logging or palm oil production, restored forests, and protected areas. In several tropical forests in Southeast Asia and South America, <50% of the forest area is primary forest, primarily due to human activities. This figure is the lowest in the Atlantic Forests of Brazil, Paraguay, and Argentina, where the value is just over 10%. In addition, Paraguay is the country that has experienced the least change in total relative forest area over the past three decades.[18]

For organizations, according to statistical data, increased productivity and efficiency, as well as customer satisfaction, are the two primary benefits that data ecosystems have contributed over the last 2–3 years. Companies that continue to work in data ecosystems expect to see around 15% annualized gains over the next 3 years.[19]

The statistics reflect the distribution of the global ecological footprint in 2015 by country.[22] The data show that the USA accounted for 12% of the global ecological footprint. The ecological footprint measures the population's demand for biological products, such as forests, infrastructure space, animal and plant products, and the supply of resources and services by ecosystems, encompassing a country's water systems and biologically productive soils.[22,23]

Forest ecosystems (forest products), agricultural products, fisheries, seafood, and other environmentally friendly supplies are important in supporting the private sector and ensuring sustainable supply chains. As of

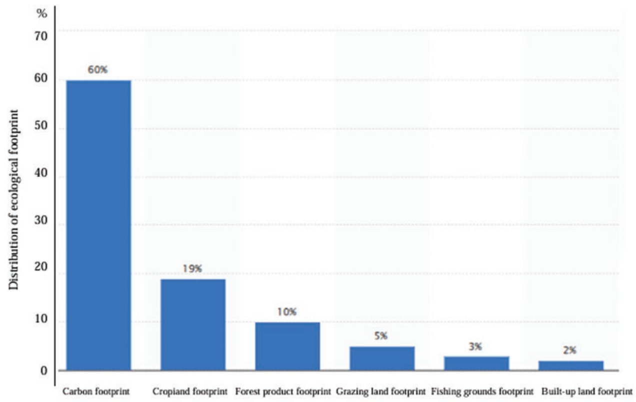

Figure 3. Distribution of humanity's ecological footprint by land use, 2020. Data sources[22-24,30]

2021, the supply was nearly US$7 billion worldwide. That highlights the importance of nature-based solutions in addressing societal risks and delivering benefits for human well-being and biodiversity.[15,23] The ecological footprint is a comparison between the demand on the biosphere for human consumption and the regenerative capacity of ecosystems.

Based on statistical data on land use (Figure 3), the largest human ecological footprint in 2020 was the carbon footprint (60%), followed by arable land (19%; food, fiber, oil, and fodder crops, including rubber), the ecological footprint of forest products (10%), and the grazing land footprint (5%).[12]

Nature's ecosystem services encompass intangible benefits that are often overlooked in traditional economic assessments. By assigning economic value to services, such as air and water purification, carbon sequestration, and biodiversity maintenance, their critical role in supporting human well-being becomes quantifiable. Economically valuing ecosystem services enables their integration into policy and decision-making. Decision-makers can comprehend the true costs and benefits of land-use changes, resource extraction, and conservation efforts, fostering more informed and sustainable choices.

Ecosystem services' economic valuation helps internalize externalities associated with environmental degradation. It sheds light on the hidden costs imposed by human activities on ecosystems, facilitating better accounting and mitigation of negative impacts.

Assessing ecosystem services economically promotes sustainable resource management. It encourages the preservation and restoration of ecosystems by recognizing their economic value, incentivizing conservation efforts, and promoting sustainable practices.

5. Conclusion

Economic evaluation of humanity's ecological footprint is crucial for informed decision-making and policy formulation. A combination of these approaches offers a comprehensive understanding of the economic implications of human-induced environmental changes. Nevertheless, ongoing refinement and integration of these methodologies are imperative to address the complexity of ecological issues within economic frameworks.

The presented legislative acts mark crucial steps toward addressing the ecological footprint. However, several areas necessitate further legislative enhancements:

(i) Climate mitigation and adaptation by strengthening international agreements and enacting robust laws to reduce greenhouse gas emissions and bolster adaptation strategies to counter climate change effects are imperative.
(ii) Legislative support for the development and implementation of eco-friendly technologies, emphasizing energy efficiency and renewable energy sources, is crucial.
(iii) Legislation should focus on safeguarding water ecosystems, reducing water pollution, and conserving water resources through effective management practices.
(iv) Encouraging sustainable production and consumption patterns through stringent laws on waste reduction, support for recycled materials, and fostering eco-conscious consumer behavior is vital.
(v) Strengthening legislation for protecting fragile ecosystems and species, particularly in forestry and marine conservation, is essential.

Enhancements in these legislative realms at both national and global levels are imperative to comprehensively address and mitigate the ecological footprint, fostering a more sustainable future for our planet.

Economically evaluating nature's ecosystem services is indispensable in capturing the true worth of nature's contributions to human well-being. It forms a crucial part in comprehensive ecological footprint assessments, providing a more accurate understanding of the environmental consequences of human actions. Recognizing and integrating these services into economic frameworks are pivotal steps toward fostering sustainable development and ensuring the preservation of essential ecosystem functions.

Recent studies in agriculture demonstrate the potential of explainable machine learning approaches for nutrient prediction, providing interpretable models that support decision-making at both farm and policy levels. Referencing such applications illustrates how AI can be employed across sectors, not only to optimize agricultural productivity but also to strengthen the credibility of ecosystem service valuation. AI methods, ecological and economic analyses gain greater interpretability, allowing stakeholders to understand the drivers of environmental outcomes and adopt sustainable practices. The integration of traditional economic and ecological assessment methods with advanced computational modeling ensures a comprehensive and scientifically robust evaluation of the ecological footprint on forest ecosystems and biodiversity.

Forests serve as critical agents in softening the ecological footprint. They sequester carbon, support biodiversity, conserve soil and water, enhance air quality, and provide essential ecosystem services. Protecting and sustainably managing forests is pivotal in mitigating the environmental impact of human activities. The current study's perspectives underscore the importance of forests as carbon sinks, the preservation of biodiversity, the understanding of nitrogen's influence on carbon storage, and the air-purification effects of trees in urban environments. In addition, this study emphasizes the critical role of ecosystems in supporting human well-being and societal functions. The conclusions highlight the multifaceted role of forests, the importance of biodiversity preservation, and the profound impact of ecosystems on environmental sustainability and human well-being.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

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