BIOENERGY AND BIOMASS IN THE GLOBAL ENERGY TRANSITION: IMPACTS OF PLANT RESOURCE EXPLOITATION ON BIOME INTEGRITY, FLORA AND FAUNA CONSERVATION, ECOSYSTEM SERVICES, AND THE LIMITS OF ENVIRONMENTAL SUSTAINABILITY IN THE FACE OF CLIMATE CHANGE

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Marcio Alexandre Botti[1], Elaine Carvalho Santana[2], Maico Danúbio Duarte Abreu[3], Fernanda Santana de Paulo[4], André Saldanha Moraes[5], Marcos Pereira Resende[6] and Ariel de Macedo Pereira do Couto[7]

Abstract

The growing demand for renewable energy sources has increased interest in the use of plant biomass as an alternative to fossil fuels, particularly given the need to reduce greenhouse gas emissions and address climate change. However, the expansion of bioenergy entails environmental contradictions associated with intensified land use, the conversion of natural ecosystems, and increasing pressure on biodiversity. This study aims to analyze the impacts of exploiting plant resources for bioenergy production on biome integrity, flora and fauna conservation, and the maintenance of ecosystem services, considering the limits of environmental sustainability in the context of the global energy transition. This is a bibliographic and documentary study adopting a qualitative, descriptive, and exploratory approach, based on scientific publications and institutional reports addressing bioenergy, climate change, biodiversity, and natural

[1] Biologist and Radiologic Technologist. Specialist in Radiation Therapy and Health Education.
E-mail: botti.17.5.30@gmail.com
[2] Biological Sciences
E-mail: elaineca891@gmail.com
[3] Teaching Degree in Physics and Mathematics, Faculdade de Tecnologia e Ciências do Norte do Paraná
E-mail: maicodanubio@yahoo.com.br
[4] Agricultural Engineer, Universidade Federal Rural do Rio de Janeiro (UFRRJ)
E-mail: fernandasant84@gmail.com
[5] Technology Degree in Public Management, final-year student, Uniasselvi
Public Servant at IFPA
E-mail: andre.saldanha@ifpa.edu.br
[6] Teaching Degree in Geography, UESPI
Teaching Degree in Natural Sciences, IFPI
Teaching Degree in Pedagogy, ETEP
Master's student in Water Resources Management and Regulation, ProfÁgua, UFPI
[7] Master's student in Civil Engineering at UFRJ
Rio de Janeiro - RJ
E-mail: ar_couto@hotmail.com
ORCID: https://orcid.org/0009-0003-2017-6070

resource management. The literature indicates that biomass can contribute to diversifying the energy mix and reducing certain emissions, particularly when derived from organic residues and appropriately managed production systems. Nevertheless, its large-scale exploitation may contribute to deforestation, habitat fragmentation, landscape simplification, soil degradation, and competition for water and land use. These processes undermine species conservation and may affect essential ecosystem services, including climate regulation, nutrient cycling, water resource protection, and the maintenance of soil fertility. The renewable nature of biomass does not, in itself, ensure its sustainability; life-cycle emissions, feedstock origin, and the territorial effects of production must also be considered. The study concludes that bioenergy's contribution to the energy transition depends on the adoption of stringent environmental criteria, territorial planning, the protection of natural ecosystems, and the prioritization of production models that reconcile emissions reduction with biodiversity conservation and socio-environmental justice.

Keywords: Biodiversity conservation, Decarbonization, Ecosystem services, Environmental sustainability, Natural resources.

INTRODUCTION

Growing concern about climate change and the need to reduce dependence on fossil fuels have driven the search for alternative energy sources in different regions of the world. In this context, bioenergy occupies an important place in discussions of the energy transition, primarily because plant-based feedstocks can be used to produce electricity, heat, and fuels. However, although bioenergy is frequently presented as a renewable alternative, its expansion raises environmental issues that extend beyond the replacement of conventional energy sources, especially when it depends on the intensive exploitation of natural resources and the expansion of areas used to cultivate energy crops.

Plant biomass comprises organic materials derived from plants, agricultural and forestry residues, and other biological sources that can be used for energy purposes. It is harnessed through various processes, including combustion, fermentation, anaerobic digestion, and thermochemical conversion. The

resulting products include ethanol, biodiesel produced from vegetable oils, biogas, and the thermal and electrical energy generated through the use of lignocellulosic residues. The diversity of these applications contributes to economic and technological interest in bioenergy, while also underscoring the need to distinguish among production systems with different characteristics and environmental impacts.

Creutzig et al. (2015) argue that bioenergy has the potential to contribute to climate change mitigation, although its benefits depend on the technologies used, the characteristics of the feedstocks, and production conditions. The authors emphasize that the expansion of biomass-based energy systems can adversely affect ecosystems, biodiversity, and living conditions when it entails high demand for land and natural resources. This understanding demonstrates that the renewable nature of an energy source does not necessarily mean that it is free from environmental impacts.

The energy transition, therefore, should not be understood merely as the replacement of fossil fuels with resources classified as renewable. It is a process involving economic, territorial, technological, and environmental transformations whose outcomes depend on the choices made in each context. In the case of bioenergy, these decisions include defining cultivation areas, selecting plant species, managing soils, using water, and determining the destination of the residues generated during production.

The Intergovernmental Panel on Climate Change (IPCC, 2022) recognizes that land-use-related mitigation measures can contribute to reducing greenhouse gas emissions. However, it emphasizes that their inappropriate implementation can exacerbate conflicts involving biodiversity conservation, food security, and the maintenance of ecosystem services. The expansion of bioenergy must therefore be assessed in conjunction with other territorial demands to prevent the pursuit of lower-carbon energy from producing new forms of environmental degradation.

One of the primary challenges associated with the exploitation of plant biomass concerns the conversion of natural ecosystems into agricultural or forestry areas intended for energy production. Replacing native vegetation formations with monocultures can profoundly alter landscape structure, reduce habitat diversity, and undermine essential ecological processes. These changes affect not only the

vegetation that is removed but also the animal populations that depend on particular environments for feeding, reproduction, movement, and shelter.

Habitat fragmentation is a significant consequence of these transformations. When natural areas are divided by productive activities, roads, or other human interventions, connectivity among populations may be reduced, hindering species movement and increasing their vulnerability to environmental change. The intensity of these effects depends on the characteristics of each biome, the extent of the interventions, and the conservation status of the remaining areas.

In this regard, flora and fauna conservation must be understood as a fundamental component of energy sustainability. Biological diversity supports processes related to pollination, seed dispersal, population regulation, and the maintenance of ecological cycles. Species loss or changes in the relationships among species may impair ecosystem functioning, even when certain areas retain vegetation cover.

Another relevant aspect concerns ecosystem services, understood as the contributions ecosystems make to human well-being and the maintenance of environmental conditions. These include climate regulation, water resource conservation, soil formation and protection, nutrient cycling, and pollination processes. Such services depend on the integrity of natural systems and may be affected by the intensive exploitation of plant resources.

The relationship between bioenergy and ecosystem services is complex. The use of certain agricultural and forestry residues can reduce waste and contribute to energy diversification. However, excessive removal of these materials can also reduce the availability of organic matter in the soil, interfere with nutrient cycling, and compromise habitat maintenance. The sustainability of energy use therefore depends not only on the renewable origin of resources but also on the intensity and conditions under which they are extracted.

The climate issue adds another dimension to this debate. The use of biomass is commonly associated with the possibility that carbon dioxide emissions may be partially offset by vegetation growth.

However, this interpretation is insufficient when it disregards emissions arising from deforestation, soil preparation, fertilizer use, transportation, and feedstock processing.

In their analysis of biofuel production and its indirect effects on land use, Searchinger et al. (2008) demonstrated the importance of considering emissions associated with the conversion of forests and other vegetation formations into agricultural areas. The study questioned assessments that attributed climate benefits to biofuels without adequately incorporating the territorial consequences of production expansion.

This discussion underscores the need to consider the life cycle of energy products, from feedstock acquisition through final use. A source may generate relatively low emissions during a particular stage of production and nevertheless cause significant impacts when land-use changes and losses of carbon stored in vegetation and soils are taken into account.

In addition to atmospheric emissions, the expansion of energy crops may intensify competition for water and arable land. In regions subject to water scarcity, the implementation of production systems with high irrigation requirements may increase pressure on rivers, reservoirs, and aquifers. Similarly, allocating extensive areas to energy production may generate conflicts with food production, environmental conservation, and the ways of life of communities that depend directly on natural resources.

These challenges take different forms depending on the ecological and socioeconomic conditions of each territory. In forest biomes, production expansion may be associated with vegetation removal and the loss of carbon stocks. In savanna and grassland formations, the conversion of natural areas may also harm species adapted to open environments, alter water regimes, and reduce ecological diversity. For this reason, environmental assessments of bioenergy cannot apply uniform criteria to ecosystems with different structures and dynamics.

In Brazil, this discussion is particularly relevant because of the country’s diversity of biomes and its historical reliance on biomass for energy purposes. The use of sugarcane, agro-industrial residues, and

various plant-based feedstocks forms part of the development trajectory of renewable energy sources in the country. However, the expansion of production chains must take into account the environmental particularities of the Amazon, the Cerrado, the Caatinga, the Atlantic Forest, the Pantanal, and the Pampa, ensuring that energy diversification does not occur at the expense of natural ecosystem degradation.

Sustainability analysis also requires attention to differences among production systems. The use of available residues, the cultivation of previously degraded areas, and the adoption of management practices that conserve soils may create environmental conditions distinct from those associated with projects that depend on converting native vegetation. Nevertheless, even these alternatives must be assessed in terms of resource availability, cumulative impacts, and the feasibility of maintaining ecological functions.

Creutzig et al. (2015) emphasize that the sustainable potential of bioenergy depends on technological, environmental, and institutional factors and that it is inappropriate to regard its expansion as a universal solution to climate change mitigation. The contribution of biomass must be examined in an integrated manner alongside other energy alternatives and ecosystem conservation strategies.

In this context, discussing the limits of environmental sustainability becomes essential. The expansion of energy production may encounter constraints related to land availability, the regenerative capacity of vegetation, the maintenance of soil fertility, and water resource conservation. Ignoring these limits entails the risk of replacing one source of environmental pressure with another without addressing the structural causes of ecosystem degradation.

The sustainability of bioenergy, therefore, should not be measured exclusively by the amount of fuel produced or the estimated reduction in emissions at a particular stage of its use. Its effects on biodiversity, carbon stocks, ecosystem services, and populations that depend on the exploited territories must also be considered. Integrating these elements enables a broader assessment of the benefits and limitations of biomass within the energy transition.

Despite the importance of renewable sources in addressing climate change, it remains necessary to understand the conditions under which the exploitation of plant resources can contribute to decarbonization without compromising environmental integrity. This issue requires recognition that different production models have different consequences and that emissions reduction cannot be separated from the protection of natural systems.

Against this backdrop, this study is delimited to the analysis of the environmental impacts associated with the exploitation of plant biomass for energy purposes, with emphasis on land-use change, biome integrity, flora and fauna conservation, and the maintenance of ecosystem services. The study also considers the limits of environmental sustainability in the face of climate change, focusing on the relationships among bioenergy production, biodiversity conservation, and natural resource management.

Based on this delimitation, the following research question is established: How can the exploitation of plant resources for bioenergy production contribute to the global energy transition without compromising biome integrity, biodiversity conservation, and the maintenance of ecosystem services in the face of climate change?

The general objective is to analyze the impacts of exploiting plant biomass for bioenergy production on biomes, flora, fauna, and ecosystem services, discussing the possibilities and limits of its sustainability in the context of the global energy transition.

The specific objectives are to understand the contribution of plant biomass to the diversification of energy sources; identify the main environmental impacts associated with the expansion of energy crops and the exploitation of plant resources; discuss the consequences of land-use change for biodiversity conservation; examine the effects of bioenergy production on ecosystem services; and analyze management and territorial planning strategies capable of reducing environmental impacts and promoting more sustainable production models.

The choice of this topic is justified by the need to deepen discussions of the environmental consequences of the energy transition. Although replacing fossil fuels is indispensable to addressing

climate change, the adoption of renewable sources requires assessments that consider their effects on ecosystems and the availability of natural resources. Energy production cannot be regarded as environmentally sound merely because it uses feedstocks of biological origin.

From a scientific perspective, this study contributes to closer integration among debates on bioenergy, climate change, and biodiversity conservation, which are often examined from different perspectives. This articulation makes it possible to understand that energy sustainability depends on complex relationships among ecological processes, production technologies, and land-use decisions.

The environmental and social relevance of the study lies in its potential to support reflection on energy policies, territorial planning, and the sustainable management of plant resources. Identifying the risks associated with biomass exploitation may contribute to decisions that take into account habitat conservation, water resource protection, and the maintenance of the ecological conditions necessary for population well-being.

Thus, discussing bioenergy within the global energy transition requires acknowledging its possibilities without disregarding the pressures its expansion may place on natural environments. The challenge lies not only in producing energy from renewable sources but also in establishing conditions under which such production does not compromise biodiversity or the ecological processes on which environmental sustainability itself depends. The energy transition can contribute consistently to addressing climate change only when it is associated with biome protection, the responsible use of natural resources, and recognition of the ecological limits of territories.

METHODOLOGY

RESEARCH DESIGN

This study is characterized as bibliographic and documentary research adopting a qualitative, descriptive, and exploratory approach. The investigation focuses on analyzing the impacts associated with the exploitation of plant biomass for bioenergy production, considering its relationship with biome

integrity, flora and fauna conservation, the maintenance of ecosystem services, and the challenges of environmental sustainability in the face of climate change.

The qualitative approach was selected because it enables interpretation of the relationships among energy production, natural resource use, and environmental conservation without restricting the analysis to quantitative indicators. According to Gil (2008), bibliographic research makes it possible to examine previously produced knowledge about a given phenomenon, while Minayo (2014) highlights the contribution of qualitative research to understanding complex processes and their different dimensions.

BIBLIOGRAPHIC AND DOCUMENTARY SURVEY PROCEDURES

The bibliographic survey was designed around scientific publications pertaining to bioenergy, plant biomass, land-use change, biodiversity conservation, and ecosystem services. SciELO, Google Scholar, and the CAPES Journals Portal (Portal de Periódicos CAPES) were selected as the databases to be consulted, using descriptors such as “bioenergy,” “plant biomass,” “energy transition,” “biodiversity,” “climate change,” “ecosystem services,” and “environmental sustainability,” as well as their equivalents in Portuguese.

The documentary research encompasses reports and institutional publications issued by international organizations, particularly the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA). These documents provide a basis for understanding the relationships among renewable energy production, greenhouse gas emissions, land use, and ecosystem conservation.

SELECTION CRITERIA AND SAMPLE COMPOSITION

Sources are selected according to their thematic relevance, scientific consistency, and contribution to the research objectives. Eligible materials include articles published in scientific journals, academic books, technical reports, and institutional documents addressing the environmental impacts of bioenergy production and the conditions necessary for its sustainability.

Duplicate materials, publications without identifiable authorship or verifiable provenance, and studies not directly related to the exploitation of plant resources for energy purposes are excluded. The bibliographic sample is purposive and comprises sources selected according to their theoretical and documentary relevance, without a predetermined number of publications.

Because this is a bibliographic and documentary review, no data will be collected directly in energy production areas, nor will experiments or field surveys be conducted.

ANALYTICAL INSTRUMENTS AND PROCEDURES

To organize the information, a bibliographic analysis matrix will be used, containing authorship, year of publication, objectives, characteristics of the biomass source, identified environmental impacts, and sustainability measures discussed in each study.

The material will be interpreted through thematic analysis based on the categorization procedures presented by Bardin (2016). The information will be organized into four thematic areas: bioenergy's contribution to the energy transition; the impacts of plant resource exploitation on biomes and biodiversity; effects on ecosystem services; and the limits of and strategies for environmental sustainability.

The discussion will seek to establish relationships among the contributions of Creutzig et al. (2015), Searchinger et al. (2008), and the IPCC (2022), considering both climate change mitigation opportunities and the risks associated with the conversion of natural ecosystems and intensified land use.

ETHICAL CONSIDERATIONS AND RESEARCH LIMITATIONS

Because it relies exclusively on bibliographic sources and publicly accessible documents, the study does not involve the direct participation of human subjects, the collection of personal data, or environmental interventions. The principles of academic integrity, source identification, and respect for the authorship of the works consulted will be observed.

Among the study's limitations is the absence of primary data on specific biomass production areas, which prevents direct measurement of impacts on species, habitats, and ecosystem services. Nevertheless, the literature analysis makes it possible to discuss the principal environmental risks associated with bioenergy and identify conditions that may support its more sustainable use.

RESULTS AND DISCUSSION

The literature on bioenergy and plant biomass demonstrates that the contribution of these sources to the energy transition depends on the environmental, technological, and territorial conditions under which production occurs. Although the use of organic materials can help diversify the energy mix and reduce certain greenhouse gas emissions, expanded production may also intensify pressures on natural ecosystems. The studies examined demonstrate that bioenergy sustainability should not be assessed solely on the basis of the renewable nature of its feedstock, but must also account for the effects of its exploitation on biodiversity, land use, and ecosystem services.

CONTRIBUTIONS OF BIOENERGY TO THE ENERGY TRANSITION

Plant biomass offers various opportunities for energy use, including the production of biofuels, electricity, and heat. The use of agricultural, forestry, and agro-industrial residues may help reduce waste and diversify energy sources, especially in systems that use materials generated by pre-existing productive activities.

Creutzig et al. (2015) emphasize that bioenergy has the potential to contribute to climate change mitigation, but that its benefits depend on feedstock characteristics, the technologies employed, and land-use conditions. Systems that use available residues may therefore have environmental consequences distinct from those requiring the expansion of large areas devoted to energy crop cultivation.

The IPCC (2022) likewise recognizes bioenergy's potential contribution to reducing emissions, while emphasizing that its implementation must account for effects on ecosystems and other territorial

demands. This perspective demonstrates that the energy transition cannot be reduced to replacing fossil fuels with renewable sources; the environmental effects of the entire production process must also be evaluated.

IMPACTS OF BIOMASS EXPLOITATION ON BIOMES AND BIODIVERSITY

The expansion of crops intended for energy production may cause significant changes in vegetation cover and landscape organization. When natural ecosystems are converted into productive areas, habitat loss, environmental fragmentation, and reductions in biological diversity may occur.

These impacts affect different groups of organisms, including plant species, birds, mammals, insects, and microorganisms associated with ecosystem functioning. Replacing natural formations with homogeneous cropping systems may alter ecological relationships and undermine processes such as seed dispersal, pollination, and population regulation.

Creutzig et al. (2015) discuss how the large-scale expansion of bioenergy may generate conflicts with biodiversity conservation and other land uses. The intensity of these consequences depends on the ecological characteristics of the occupied areas and the management practices employed.

In the Brazilian context, this discussion is particularly important given the diversity of biomes and the various pressures associated with the expansion of agricultural activities. Using previously degraded areas may reduce the need to convert native vegetation, but it does not eliminate the importance of assessing effects on soils, water resources, and habitat connectivity.

EFFECTS ON ECOSYSTEM SERVICES

Ecosystem services are the contributions ecosystems make to maintaining environmental conditions and human well-being. They include climate regulation, water resource conservation, soil formation, nutrient cycling, and the maintenance of essential ecological processes.

The intensive exploitation of biomass may compromise these services when it involves excessive removal of plant residues, the replacement of natural ecosystems, or inappropriate use of water resources. The continuous removal of organic materials, for example, may reduce nutrient availability and affect the maintenance of soil organic matter, depending on management conditions.

The IPCC (2022) emphasizes that land-use-related mitigation measures must account for their effects on biodiversity, ecosystems, and food security. This guidance reinforces the need to understand bioenergy production as an activity integrated with the environmental processes of the territories in which it occurs.

Maintaining ecosystem services is therefore an important criterion for assessing biomass sustainability. Production systems that preserve native vegetation, maintain soil cover, and use natural resources in a planned manner tend to offer more favorable conditions for environmental conservation than systems based on intensive exploitation and habitat conversion.

CARBON EMISSIONS AND THE LIMITS OF CLIMATE SUSTAINABILITY

One of the main arguments in favor of bioenergy use concerns its potential to reduce greenhouse gas emissions. However, assessing its climate benefits requires consideration of emissions generated throughout the entire chain, including cultivation, processing, transportation, and land-use change.

Searchinger et al. (2008) demonstrated that the expansion of certain biofuels may generate additional emissions when it directly or indirectly encourages the conversion of natural ecosystems into agricultural areas. This contribution shows that reducing emissions during fuel use does not necessarily produce a climate benefit when territorial transformations associated with production are disregarded.

Life-cycle analysis is therefore indispensable to comparing different energy alternatives. Feedstock origin, the intensity of fertilizer use, transportation requirements, and the preservation of carbon stocks in vegetation and soils all influence environmental outcomes.

The literature discussed indicates that the climate sustainability of bioenergy depends on specific conditions and that the same benefits cannot be attributed to all biomass sources. The use of residues and production in previously occupied areas may offer advantages in certain contexts, provided that they do not cause additional degradation or compromise important ecological functions.

STRATEGIES FOR SUSTAINABLE BIOENERGY PRODUCTION

Reducing the environmental impacts of bioenergy requires territorial planning, feedstock selection criteria, and management practices compatible with ecosystem conservation. The possibilities discussed in the literature include the responsible use of residues, the protection of native vegetation, the use of areas suitable for production, and the adoption of technologies that improve energy efficiency.

Creutzig et al. (2015) emphasize that bioenergy's contribution to climate change mitigation depends on technological and institutional choices, as well as on the environmental conditions under which production occurs. Sustainability must therefore be considered from the planning of activities through the evaluation of their outcomes.

Table 1 summarizes the principal benefits, risks, and sustainability conditions associated with the exploitation of plant biomass.

Table 1

Potential benefits, environmental impacts, and sustainability conditions of bioenergy

Dimension	Potential benefits	Impacts and risks	Sustainability conditions
Energy transition	Diversification of the energy mix and partial replacement of fossil fuels	Emissions associated with production and transportation	Life-cycle assessment and energy efficiency
Land use	Use of existing productive areas	Ecosystem conversion and territorial competition	Territorial planning and protection of native vegetation
Biodiversity	Potential integration with diversified production systems	Habitat loss and environmental fragmentation	Conservation of natural areas and ecological connectivity
Soils	Energy use of a portion of plant residues	Loss of organic matter and nutrients due to excessive removal	Management of residual biomass and soil conservation
Water resources	Use of residues from existing activities	Increased demand for water and changes in water quality	Efficient water management and protection of water sources
Climate change	Potential emissions reductions under specific conditions	Emissions resulting from direct and indirect land-use change	Emissions control and preservation of carbon stocks

Source: Prepared based on Searchinger et al. (2008), Creutzig et al. (2015), and the IPCC (2022).

The synthesis demonstrates that the environmental benefits of bioenergy depend on factors extending beyond energy-generation capacity. The origin of plant resources, production conditions, and effects on ecosystems must be considered jointly to prevent the expansion of renewable sources from causing new forms of degradation.

Overall, the discussion indicates that biomass can contribute to the global energy transition, but its sustainability should not be presumed. Biodiversity conservation, the maintenance of ecosystem services, and effective emissions reductions are essential conditions for bioenergy production to be compatible with addressing climate change and protecting natural resources.

CONCLUSION

This study aimed to analyze the impacts of exploiting plant biomass for bioenergy production on biome integrity, flora and fauna conservation, and the maintenance of ecosystem services, considering the limits of environmental sustainability in the face of climate change. The discussion showed that the use of

plant resources as an energy source offers significant opportunities to diversify the global energy mix, but that its benefits depend on the environmental, technological, and territorial conditions under which production occurs.

The literature analysis demonstrated that bioenergy can contribute to the partial replacement of fossil fuels and the reduction of certain greenhouse gas emissions, particularly when it involves the responsible use of agricultural, forestry, and agro-industrial residues. However, these advantages are not uniform, as different feedstocks and production processes generate different impacts. Biomass origin, management practices, and land-use changes are decisive factors in determining environmental outcomes.

The primary challenges identified include the conversion of natural ecosystems into energy production areas, habitat fragmentation, loss of biological diversity, and intensified demand for land and water resources. These transformations may compromise the conservation of plant and animal species, alter ecological relationships, and affect the balance of biomes. When undertaken without adequate planning, the expansion of energy monocultures may also promote landscape simplification and increase the vulnerability of environments to climate pressures.

The study also demonstrated the importance of considering ecosystem services when assessing biomass sustainability. Soil conservation, climate regulation, water resource protection, and the maintenance of nutrient cycles are directly related to ecosystem integrity. The intensive exploitation of plant materials, particularly when it involves excessive residue removal or the replacement of natural cover, may compromise these functions and reduce the capacity of environments to respond to climate change.

Another relevant consideration is the need to assess emissions throughout the entire production chain. The renewable nature of biomass does not, in itself, ensure carbon neutrality, since cultivation, processing, transportation, and direct or indirect land-use changes may generate significant emissions. Bioenergy's climate contribution must therefore be analyzed using criteria that account for the life cycle of energy products and the preservation of carbon stocks in vegetation and soils.

The principal contribution of this study lies in reinforcing the understanding that bioenergy sustainability cannot be defined solely by the capacity to produce energy from renewable sources. By linking the energy transition, biodiversity, ecosystem services, and climate change, the research highlights the need to integrate energy and environmental policies, thereby preventing decarbonization strategies from imposing new pressures on natural resources.

In this regard, territorial planning, the protection of native vegetation, the responsible use of residues, and the adoption of production practices compatible with ecosystem characteristics are important means of reducing environmental impacts. However, these measures require monitoring, continuous evaluation, and sustainability criteria capable of accounting for the particularities of each territory.

For future research, comparative studies are suggested on the impacts of different biomass sources in Brazilian biomes, particularly the Amazon, the Cerrado, and the Caatinga. Research into changes in biodiversity, water availability, soil conservation, and carbon emissions in energy production systems is also relevant, as are assessments of the socio-environmental effects of expanding crops intended for biofuel production.

It is concluded that bioenergy can form part of climate change response strategies, provided that its expansion respects ecological limits and does not compromise the conservation of natural environments. The energy transition represents an opportunity to reorganize energy production and consumption systems, but its outcomes will depend on the capacity to reconcile emissions reduction with the protection of biomes, fauna, flora, and ecosystem services. An environmentally sustainable energy mix therefore requires not only renewable sources but also decisions guided by biodiversity conservation, the responsible use of natural resources, and responsibility toward present and future generations.

REFERENCES

Bardin, Laurence. *Análise de conteúdo* [Content analysis]. São Paulo: Edições 70, 2016.

Cherubini, Francesco; Strømman, Anders Hammer. Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresource Technology*, v. 102, n. 2, p. 437–451, 2011. DOI: https://doi.org/10.1016/j.biortech.2010.08.010.

Creutzig, Felix et al. Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*, v. 7, n. 5, p. 916–944, 2015. DOI: https://doi.org/10.1111/gcbb.12205.

Fargione, Joseph et al. Land clearing and the biofuel carbon debt. *Science*, v. 319, n. 5867, p. 1235–1238, 2008. DOI: https://doi.org/10.1126/science.1152747.

Foley, Jonathan A. et al. Solutions for a cultivated planet. *Nature*, v. 478, p. 337–342, 2011. DOI: https://doi.org/10.1038/nature10452.

Gil, Antonio Carlos. *Métodos e técnicas de pesquisa social* [Methods and techniques of social research]. 6. ed. São Paulo: Atlas, 2008.

IPCC – Intergovernmental Panel on Climate Change. *Climate change 2022*: mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2022. DOI: https://doi.org/10.1017/9781009157926.

Millennium Ecosystem Assessment. *Ecosystems and human well-being*: synthesis. Washington, DC: Island Press, 2005.

Minayo, Maria Cecília de Souza. *O desafio do conhecimento*: pesquisa qualitativa em saúde [The challenge of knowledge: qualitative research in health]. 14. ed. São Paulo: Hucitec, 2014.

Rockström, Johan et al. A safe operating space for humanity. *Nature*, v. 461, p. 472–475, 2009. DOI: https://doi.org/10.1038/461472a.

Searchinger, Timothy et al. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, v. 319, n. 5867, p. 1238–1240, 2008. DOI: https://doi.org/10.1126/science.1151861.

Tilman, David et al. Beneficial biofuels: the food, energy, and environment trilemma. *Science*, v. 325, n. 5938, p. 270–271, 2009. DOI: https://doi.org/10.1126/science.1177970.