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Planetary Pressures-Adjusted Human Development Index in the States of Brazil

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Abstract

The Anthropocene era demands a fundamental reassessment of development metrics that account for planetary boundaries and environmental sustainability. This study presents an adaptation of the Planetary Pressures-Adjusted Human Development Index (PHDI) to Brazilian states, integrating environmental pressures into human development assessment. Using the Brazilian Human Development Index (BHDI) calculated by the João Pinheiro Foundation in partnership with UNDP-Brazil office, we incorporate greenhouse gas emissions data and material footprint to adjust development rankings according to environmental costs. The analysis reveals substantial ranking transformations when planetary pressures are considered: while the Federal District and São Paulo maintain leadership positions, states like Mato Grosso experience dramatic declines from 11th to 27th position, reflecting intensive agricultural activities and deforestation. Conversely, several Northeast states demonstrate improved rankings, suggesting more sustainable development patterns. The Center-West and Amazon regions emerge as areas with disproportionate environmental pressures relative to their human development levels. These findings underscore the critical need for development strategies that balance human welfare with ecological sustainability, particularly in regions facing intensive resource extraction and land use changes. The study provides essential insights for policymakers seeking to implement sustainable development approaches that respect planetary boundaries while promoting human welfare.

Keywords: Human Development Index; Planetary Pressures; Anthropocene; Greenhouse Gas Emissions; Sustainable Development; Brazil

Introduction

The COVID-19 pandemic experience illustrated an alarming truth long predicted by the scientific community: zoonotic pandemics, in which pathogens transition from animals to humans, are a direct consequence of our intensive exploitation of the environment (Taylor et al. 2001). This health crisis reflects the proposal of a new geological era, the Anthropocene, defined by human influence over the planet,

occurring at an unprecedented scale, speed, and scope (Zalasiewicz et al. 2019). At the same time, the pandemic highlighted and exacerbated pre-existing global inequalities, making it clear that crises, while universal, have disproportionate impacts, affecting those in vulnerable situations more severely. In this context, COVID-19 is not only a public health crisis but also an acute symptom of the ecological and social imbalances fueled by disparities in wealth and power around the world (UNDP 2020).

The concept of the Anthropocene extends beyond geological classification to encompass fundamental challenges to traditional development paradigms. As Zalasiewicz et al. (2017) argue, human activities have become the dominant force shaping Earth's systems, from climate patterns to biodiversity loss, from biogeochemical cycles to landscape transformation. This reality demands a comprehensive reevaluation of how societies measure progress and define development success. The traditional metrics that have guided development policy for decades increasingly appear inadequate for addressing the complex challenges of the 21st century, where human welfare and planetary health are inextricably linked.

In this context, COVID-19 emerges not merely as a public health emergency but as an acute manifestation of the ecological and social imbalances generated by development models that prioritize short-term economic gains over long-term sustainability (UNDP 2020). The pandemic has revealed how environmental degradation, social inequality, and economic vulnerability interact to create systemic risks that transcend national boundaries and traditional policy domains. These interconnected challenges require new approaches to development that can simultaneously address human welfare and environmental sustainability.

The Human Development Index (HDI), introduced by the United Nations Development Programme in 1990, represented a paradigmatic shift in development thinking by focusing on fundamental elements of human welfare rather than purely economic indicators. By incorporating health, education, and income dimensions, the HDI offered a more comprehensive assessment of societal progress than traditional measures such as Gross Domestic Product per capita. This approach has significantly influenced public discourse and policy formulation worldwide, providing a framework for understanding development that extends beyond material wealth to encompass basic human capabilities and freedoms.

However, despite its contributions to development thinking and subsequent expansions to incorporate factors such as inequality, gender disparities, and multidimensional poverty, the HDI framework has been increasingly criticized for its failure to account for environmental costs and planetary boundaries (UNDP 2020). The index's components, while capturing important aspects of human welfare, do not reflect the pressures that development activities exert on Earth's systems. This limitation has become particularly problematic in the Anthropocene era, where the sustainability of development pathways depends critically on their environmental impacts.

The recognition of these limitations has prompted efforts to develop more comprehensive development metrics that integrate environmental considerations.

The concept of planetary boundaries, introduced by Rockström et al. (2009), provides a framework for understanding the safe operating space for humanity within Earth's systems. This approach identifies nine critical Earth system processes and establishes quantitative boundaries that, if transgressed, could lead to abrupt or irreversible environmental changes that would undermine human welfare. The planetary boundaries framework has gained significant traction in sustainability science and policy circles, providing a scientific foundation for development approaches that respect ecological limits.

Building on these insights, the United Nations Development Programme has proposed the Planetary Pressures-Adjusted Human Development Index (PHDI) as a methodology for integrating environmental considerations into human development assessment (UNDP 2020). The PHDI represents an attempt to harmonize high performance in traditional development indicators with reduced ecological footprint, addressing the growing recognition that sustainable development must operate within planetary boundaries. This approach acknowledges that development gains achieved at the expense of environmental sustainability may ultimately prove self-defeating, undermining the very foundations upon which human welfare depends.

The PHDI methodology incorporates environmental impacts through a corrective factor based on per capita carbon dioxide emissions and per capita material footprint. This dual approach recognizes that different development pathways can achieve similar levels of human welfare while imposing vastly different environmental costs across multiple dimensions of planetary pressure. By making these costs explicit in development assessment, the PHDI aims to encourage development strategies that maximize human welfare while minimizing environmental impact across both climate and resource consumption dimensions.

In the Brazilian context, human development assessment has been adapted to local conditions through the Brazilian Human Development Index (BHDI), calculated by the João Pinheiro Foundation in partnership with UNDP and the Institute for Applied Economic Research (IPEA). The BHDI applies HDI methodology to Brazilian municipalities and states, providing detailed insights into development patterns across the country's diverse regions and administrative units. This localized approach has proven valuable for understanding regional development disparities and informing targeted policy interventions.

Brazil's vast territory, diverse ecosystems, and complex development challenges make it an ideal case study for applying planetary pressures-adjusted development metrics. The country encompasses multiple biomes, from the Amazon rainforest to the Cerrado savanna, each facing distinct environmental pressures from development activities. Brazil's economy combines advanced industrial and service sectors with extensive agricultural and extractive activities, creating a complex landscape of development patterns with varying environmental implications across both emissions and resource consumption dimensions.

The present study aims to adapt the PHDI methodology to the Brazilian context, applying it to the country's 27 states to assess how comprehensive environmental

pressures affect development rankings and reveal patterns of sustainable and unsustainable development. This analysis builds on the BHDI framework while incorporating both greenhouse gas emissions and material footprint data to adjust development assessments according to environmental costs. The study seeks to provide policymakers, researchers, and civil society organizations with tools for understanding the environmental dimensions of development and identifying pathways toward more sustainable development models.

This article is organized into six main sections that systematically develop the theoretical framework, methodology, and empirical findings of our planetary pressures-adjusted human development analysis. Following this introduction, the second section presents the theoretical framework underlying the Planetary Pressures-Adjusted Human Development Index, examining the conceptual foundations of planetary boundaries and their integration with human development assessment. The third section details our methodology and data sources, describing the adaptation of PHDI methodology to Brazilian states and the integration of environmental data from national monitoring systems. The fourth section presents our empirical results and analysis, revealing the dramatic ranking transformations that occur when environmental pressures are incorporated into development assessment. The fifth section discusses the broader implications of our findings for sustainable development theory and policy, examining both methodological contributions and policy recommendations for Brazilian development strategy. The final section concludes with a synthesis of key findings and directions for future research in planetary pressures-adjusted development assessment.

Theoretical Framework: Planetary Pressures-Adjusted Human Development Index

The Planetary Pressures-Adjusted Human Development Index emerges from the recognition that traditional development metrics inadequately capture the environmental costs of human progress. The PHDI represents a methodological innovation that attempts to reconcile high human development performance with ecological sustainability, addressing a fundamental tension in contemporary development thinking (UNDP 2020). This approach builds on decades of research in ecological economics, environmental sociology, and sustainability science that have highlighted the limitations of growth-oriented development models.

The theoretical foundation of the PHDI rests on several key concepts that have evolved within sustainability science. The notion of planetary boundaries provides a scientific framework for understanding the safe operating space for humanity within Earth's systems (Rockström et al. 2009). This concept identifies nine critical Earth system processes, including climate change, biodiversity loss, biogeochemical flows, and land-system change, each with quantitative boundaries that define safe operating limits. Transgressing these boundaries increases the risk of generating large-scale abrupt or irreversible environmental changes that could undermine human welfare and development prospects.

The PHDI methodology specifically focuses on two critical planetary pressures: carbon dioxide emissions and material footprint. These indicators were selected based on their significance for global environmental sustainability and their capacity to capture different dimensions of environmental pressure (UNDP 2020). Carbon dioxide emissions represent the primary driver of anthropogenic climate change, while material footprint captures the broader resource consumption patterns that drive environmental degradation across multiple Earth system processes, including biodiversity loss, land use change, and resource depletion.

Carbon Dioxide Emissions and Climate Pressures

Carbon dioxide represents the most significant anthropogenic greenhouse gas in terms of cumulative climate impact, accounting for approximately 76% of total greenhouse gas emissions globally (SEEG 2022). While other greenhouse gases such as methane and nitrous oxide have higher warming potential per molecule, CO_2 dominates due to the scale of emissions and its long atmospheric lifetime. The concentration of atmospheric CO_2 has increased from pre-industrial levels of approximately 280 parts per million to over 410 parts per million in 2021, representing the highest levels in over 3 million years.

The relationship between CO_2 emissions and development patterns reflects fundamental characteristics of economic systems and energy use. Historically, economic growth has been closely coupled with fossil fuel consumption and associated CO_2 emissions, creating what economists term the "carbon intensity" of economic activity (FJP 2025). However, this relationship is not fixed, and significant variations exist across countries and regions in the carbon efficiency of development processes. Some economies have achieved substantial improvements in human welfare with relatively modest increases in emissions, while others have generated high emissions for limited development gains.

In the Brazilian context, CO_2 emissions patterns reflect the country's diverse economic structure and regional development characteristics. Brazil's emissions profile differs significantly from developed countries, with substantial contributions from land use change and forestry alongside more traditional sources such as energy production and industrial processes (SEEG 2022). The country's extensive agricultural sector and ongoing deforestation in regions such as the Amazon and Cerrado contribute significantly to national emissions, creating distinct regional patterns that reflect different development models and economic activities.

Material Footprint and Resource Consumption Patterns

The material footprint represents the total amount of raw materials extracted globally to meet the final consumption demands of a country or region (FJP 2025). This indicator provides a comprehensive measure of resource use that extends beyond territorial extraction to include the materials embodied in traded goods. The material footprint concept recognizes that modern economies are characterized by complex global supply chains that can obscure the true resource requirements of consumption patterns.

The calculation of material footprint involves sophisticated accounting methods that trace material flows through global supply chains. The methodology distinguishes between domestic material consumption, which measures the physical materials used within a territory, and material footprint, which attributes global material extraction to final consumption regardless of where extraction occurs (FJP 2025). This distinction is crucial for understanding the true environmental impact of different consumption patterns and development models.

Material footprint encompasses four major categories of materials: biomass, fossil fuels, metal ores, and non-metallic minerals. Each category represents different types of environmental pressures and resource constraints. Biomass extraction affects land use patterns and ecosystem services, fossil fuel extraction drives climate change and local environmental degradation, metal ore extraction often involves significant landscape disruption and pollution, and non-metallic mineral extraction supports construction and infrastructure development but can have substantial local environmental impacts.

The relationship between material footprint and human development reflects the resource intensity of different development pathways. Traditional development models often assume that higher material consumption is necessary for improved human welfare, but empirical evidence suggests that this relationship is more complex (UNDP 2020). Some countries achieve high levels of human development with relatively modest material footprints, while others consume large quantities of materials for limited welfare gains. Understanding these patterns is crucial for identifying sustainable development pathways that can meet human needs within planetary resource constraints.

PHDI Calculation Methodology

The PHDI is calculated as the product of the traditional HDI and an adjustment factor that reflects planetary pressures (UNDP 2020). The adjustment factor is derived from the arithmetic average of normalized indices for per capita CO_2 emissions and per capita material footprint. This approach assumes perfect substitutability between the two environmental indicators, meaning that high performance on one indicator can compensate for poor performance on the other.

The mathematical formulation of the PHDI can be expressed as:

$$PHDI = HDI \times (1 - Planetary\ Pressures\ Index)$$

where the Planetary Pressures Index represents the arithmetic average of the normalized CO_2 emissions index and the normalized material footprint index. The normalization process scales both indicators to a range between 0 and 1, where 0 represents the minimum observed value and 1 represents the maximum observed value across all countries or regions in the analysis.

This methodology has several important implications for interpretation. Countries or regions with high environmental pressures will experience larger adjustments to their

HDI scores, potentially resulting in significant ranking changes. Conversely, areas with low environmental pressures may see their relative positions improve when the adjustment is applied. The magnitude of these changes depends on both the absolute level of environmental pressures and the distribution of pressures across the comparison group.

Methodology and Brazilian Data Sources

Brazil has developed a sophisticated adaptation of the global Human Development Index through the Brazilian Human Development Index (BHDI), which represents one of the most comprehensive subnational applications of HDI methodology worldwide (FJP/PNUD 2023). The BHDI is calculated through a partnership between the United Nations Development Programme – Brazil office (UNDP), the João Pinheiro Foundation (FJP), and the Institute for Applied Economic Research (IPEA), reflecting a collaborative approach that combines international expertise with local knowledge and data capabilities.

The BHDI methodology adapts the global HDI framework to Brazilian conditions while maintaining certain comparability with international standards. The index incorporates three fundamental dimensions of human development: longevity, education, and income. However, the specific indicators and calculation methods have been adjusted to reflect Brazilian data availability and policy priorities (FJP/PNUD 2023). For longevity, the index uses life expectancy at birth calculated from vital statistics and demographic projections. The education dimension combines literacy rates and school enrollment data, with specific attention to different educational levels relevant to Brazilian educational policy. The income dimension utilizes per capita household income data adjusted for regional cost-of-living differences.

In census years, the BHDI is calculated for all Brazilian municipalities using comprehensive data from the Demographic Census conducted by the Brazilian Institute of Geography and Statistics (IBGE). This approach provides detailed coverage of the country's 5,570 municipalities, offering unprecedented granularity for understanding development patterns across Brazil's diverse territories in the years 1991, 2000, and 2010 (data for 2022 will be available following the release of the Census Demography results). The census-based calculation ensures high data quality and comprehensive coverage, making the BHDI a valuable tool for policy formulation and resource allocation at multiple administrative levels. In non-census years, it is calculated using the Continuous National Household Sample Survey (PNADC), also conducted by the IBGE. This produces the index for all states and metropolitan regions included in the survey's sampling plan, referred to as the BHDI Radar, available since 2012, which provides the data used in the present study.

Environmental Data Integration

The assessment of environmental pressures in Brazil relies on comprehensive data systems that capture both greenhouse gas emissions and material consumption patterns. For greenhouse gas emissions, the study utilizes data from the Greenhouse

Gas Emissions and Removals Estimation System (SEEG), which represents the most comprehensive and systematic effort to quantify emissions across Brazilian territories and economic sectors (SEEG 2022).

SEEG methodology follows international standards established by the Intergovernmental Panel on Climate Change (IPCC) while adapting to Brazilian data availability and institutional contexts. The system organizes emissions data into five major sectoral categories: Agriculture, Energy, Industrial Processes and Product Use (IPPU), Waste, and Land Use and Forests (LUCF). This sectoral approach enables detailed analysis of emissions sources and supports targeted policy interventions.

For material footprint assessment, the study employs estimation methods developed by FJP that combine domestic extraction data with interstate trade flow analysis (FJP 2025). The methodology begins with compilation of domestic extraction data for each state, including biomass from agriculture and forestry, fossil fuels, metal ores, and non-metallic minerals. This information is available from various IBGE surveys, providing comprehensive coverage of domestic material extraction across Brazilian states.

The estimation of interstate material flows utilizes regional supply and use tables to identify monetary flows between states and sectors, then applies conversion factors to estimate physical quantities. These conversion factors represent established relationships between monetary values and physical quantities for different types of goods, enabling the estimation of the physical content of interstate trade based on monetary flow data. This approach provides the most comprehensive framework currently available for estimating material consumption patterns at the state level.

PHDI Calculation for Brazilian States

The adaptation of PHDI methodology to Brazilian states follows the global framework while incorporating the specific data sources and characteristics of the Brazilian context. The calculation begins with state-level BHDI values, which serve as the foundation for adjustment based on environmental pressures. These BHDI values are calculated using the established methodology developed by the João Pinheiro Foundation and partners, ensuring consistency with previous analyses and policy applications.

The environmental adjustment factor incorporates both per capita CO_2 emissions data from SEEG and per capita material footprint estimates from FJP analysis. Per capita emissions are calculated by dividing total state emissions by state population, providing a measure of the carbon intensity of development in each state. Similarly, per capita material footprint is calculated by dividing total state material consumption by population, reflecting the resource intensity of development patterns.

The normalization process scales both environmental indicators to a range between 0 and 1, where 0 represents the state with the lowest environmental pressure and 1 represents the state with the highest pressure for each indicator. The planetary pressures index is then calculated as the arithmetic average of the normalized

emissions and material footprint indices. The adjustment factor is calculated as (1 – planetary pressures index), so that states with higher environmental pressures receive larger downward adjustments to their BHDI scores.

The final PHDI calculation multiplies the original BHDI by the adjustment factor, producing adjusted development scores that incorporate comprehensive environmental considerations. The magnitude of adjustment varies across states depending on their environmental pressure levels relative to the national distribution. States with pressures below the national average may see their relative positions improve, while those with above-average pressures typically experience ranking declines.

Results and Analysis

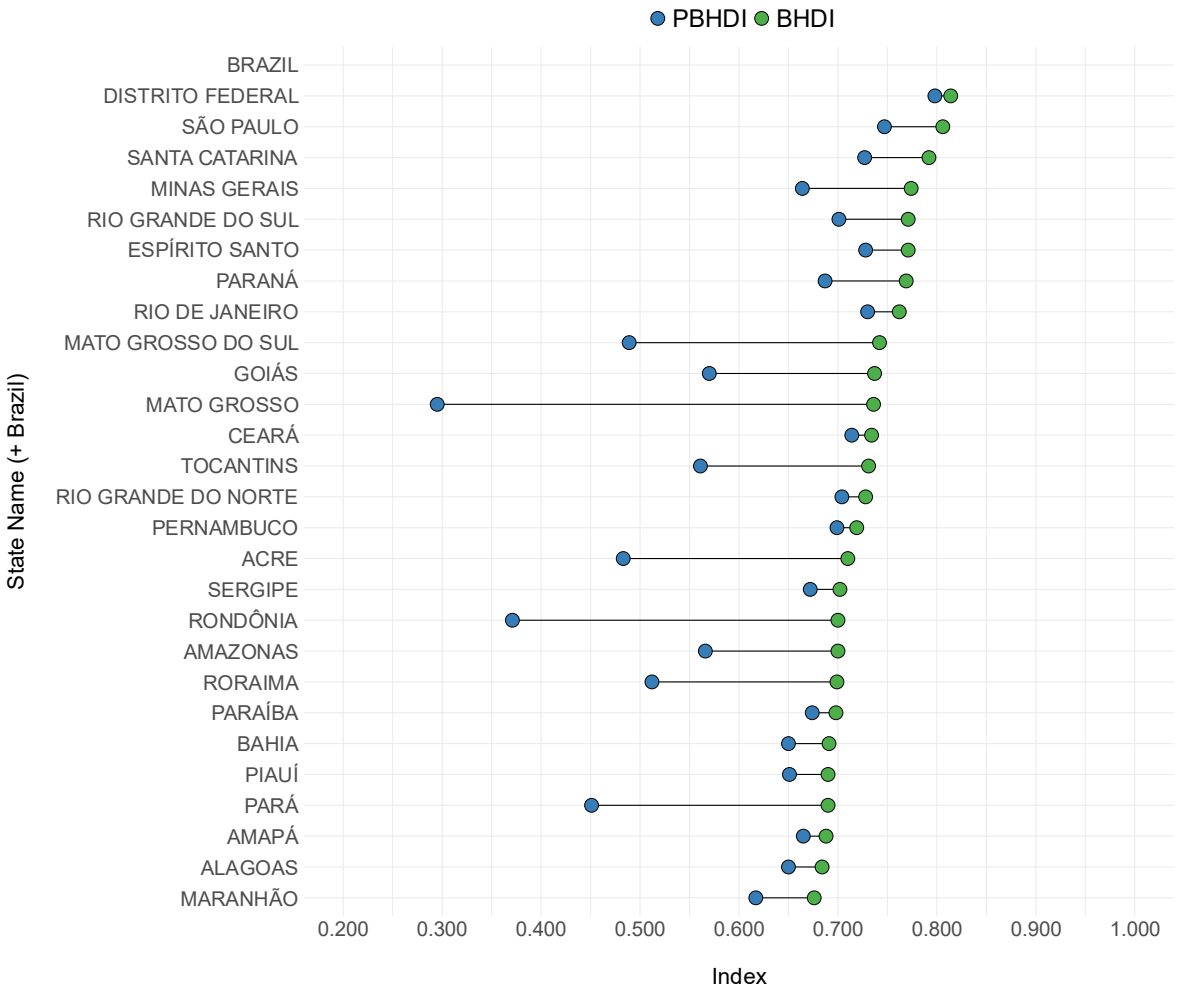
The 2021 Brazilian Human Development Index (BHDI) rankings reveal a clear hierarchy of human development across Brazilian states, with the Federal District leading at 0.814, followed by São Paulo (0.806), Santa Catarina (0.792), and Minas Gerais (0.774). These four states represent the highest levels of human development in the country, demonstrating superior performance across the health, education, and income dimensions that comprise the index. The Federal District's exceptional performance can be attributed to its unique characteristics as the national capital, concentrating federal government activities and elevated income levels. São Paulo, as Brazil's economic powerhouse, maintains its second position through its robust industrial base, extensive service sector, and significant urban infrastructure.

At the lower end of the spectrum, Maranhão (0.676), Alagoas (0.684), Amapá (0.688), and Piauí (0.690) occupy the bottom four positions in the BHDI ranking. These states, predominantly located in the Northeast and North regions, face persistent challenges in improving educational outcomes, healthcare access, and income generation opportunities for their populations.

The application of planetary pressures adjustments through the Planetary Pressures-Adjusted Brazilian Human Development Index (PBHDI) reveals dramatic shifts in state rankings, fundamentally altering our understanding of sustainable development across Brazil. The Federal District and São Paulo maintain their leadership positions with PBHDI values of 0.798 and 0.747 respectively, demonstrating that these states achieve high human development while maintaining relatively controlled environmental pressures. However, the stability at the top masks significant turbulence in the middle and lower tiers of the ranking system.

The most striking transformation occurs with Mato Grosso, which experiences the most dramatic decline in the entire ranking system. From its 11th position in BHDI (0.736), the state plummets to 27th place in PBHDI (0.295), representing a drop of 16 positions. This massive decline reflects the state's intensive agricultural activities, particularly soybean cultivation and cattle ranching, which generate substantial greenhouse gas emissions through deforestation, land use changes, and livestock methane production.

Figure 1: BHDI and PBHDI for Brazilian States - 2021



Source: UNDP-Brazil/FJP/Ipea and author's own calculations.

The Center-West region emerges as the most severely impacted by planetary pressures adjustments, with multiple states experiencing substantial ranking deteriorations. Mato Grosso do Sul falls from 9th to 23rd position (a decline of 14 positions), while Goiás drops from 10th to 19th place (a decline of 9 positions). These patterns reflect the region's role as Brazil's agricultural frontier, where intensive farming practices and land use changes generate significant environmental pressures.

The Amazon region also demonstrates considerable vulnerability to planetary pressures adjustments. Acre experiences a notable decline from 16th to 24th position (8 positions), while Rondônia falls from 18th to 26th place (8 positions). These declines underscore the environmental costs associated with deforestation, agricultural expansion, and resource extraction activities that characterize much of the Amazon's economic development model.

Figure 2: BHDI and PBHDI Rankings for Brazilian States - 2021

Brazilian Human Development Index (BHDI) and
Planetary pressures-adjusted Brazilian Human Development Index (PBHDI)
Ranking - 2021

State Name	BHDI	BHDI - Ranking	PBHDI	PBHDI - Ranking	Diff
DISTRITO FEDERAL	0.814	1	0.798	1	= 0
SÃO PAULO	0.806	2	0.747	2	= 0
SANTA CATARINA	0.792	3	0.727	5	-2
MINAS GERAIS	0.774	4	0.664	14	-10
ESPÍRITO SANTO	0.771	5	0.728	4	1
RIO GRANDE DO SUL	0.771	5	0.701	8	-3
PARANÁ	0.769	7	0.687	10	-3
RIO DE JANEIRO	0.762	8	0.730	3	5
MATO GROSSO DO SUL	0.742	9	0.489	23	-14
GOIÁS	0.737	10	0.570	19	-9
MATO GROSSO	0.736	11	0.295	27	-16
CEARÁ	0.734	12	0.714	6	6
TOCANTINS	0.731	13	0.561	21	-8
RIO GRANDE DO NORTE	0.728	14	0.704	7	7
PERNAMBUCO	0.719	15	0.699	9	6
ACRE	0.710	16	0.483	24	-8
SERGIPE	0.702	17	0.672	12	5
AMAZONAS	0.700	18	0.566	20	-2
RONDÔNIA	0.700	18	0.371	26	-8
RORAIMA	0.699	20	0.512	22	-2
PARAÍBA	0.698	21	0.674	11	10
BAHIA	0.691	22	0.650	16	6
PARÁ	0.690	23	0.451	25	-2
PIAUÍ	0.690	23	0.651	15	8
AMAPÁ	0.688	25	0.665	13	12
ALAGOAS	0.684	26	0.650	16	10
MARANHÃO	0.676	27	0.617	18	9

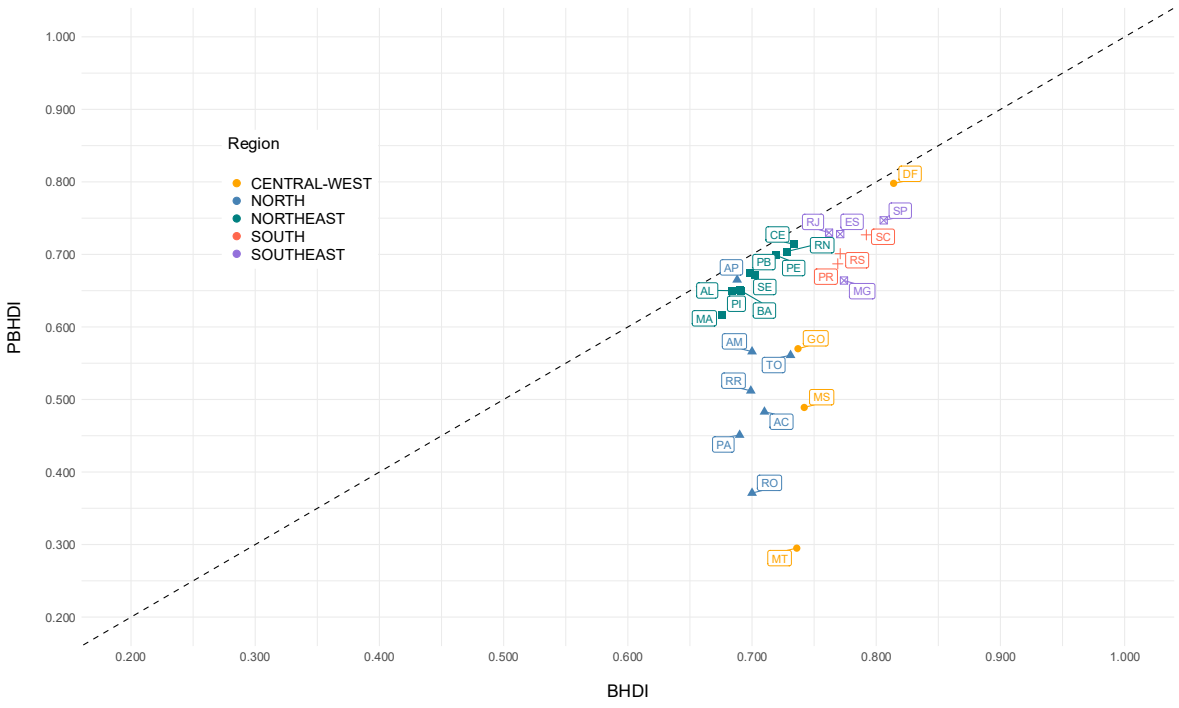
Source: UNDP-Brazil/FJP/Ipea and author's own calculations.

Conversely, several states demonstrate remarkable resilience or even improvement when environmental factors are incorporated. Paraíba achieves the most significant positive adjustment, rising from 21st to 11th position (an improvement of 10 positions), suggesting that the state maintains relatively low environmental pressures while achieving moderate human development levels.

The correlation analysis between BHDI and PBHDI reveals distinct clusters of states based on their environmental efficiency in achieving human development. States positioned above the diagonal line in the correlation graph demonstrate superior environmental performance relative to their human development levels, while those below the line indicate higher environmental costs for their achieved development.

The Northeast region shows a generally positive pattern, with states like Pernambuco (rising 6 positions), Sergipe (rising 5 positions), and Bahia (rising 6 positions) demonstrating that lower-income regions can achieve relatively sustainable development patterns. This suggests that these states, while facing human development challenges, maintain development models with lower environmental intensity. This variation suggests that development strategies, economic structures, and environmental policies significantly influence the relationship between human development and planetary pressures.

Figure 3: Relation between BHDI and PBHDI across Brazilian States - 2021

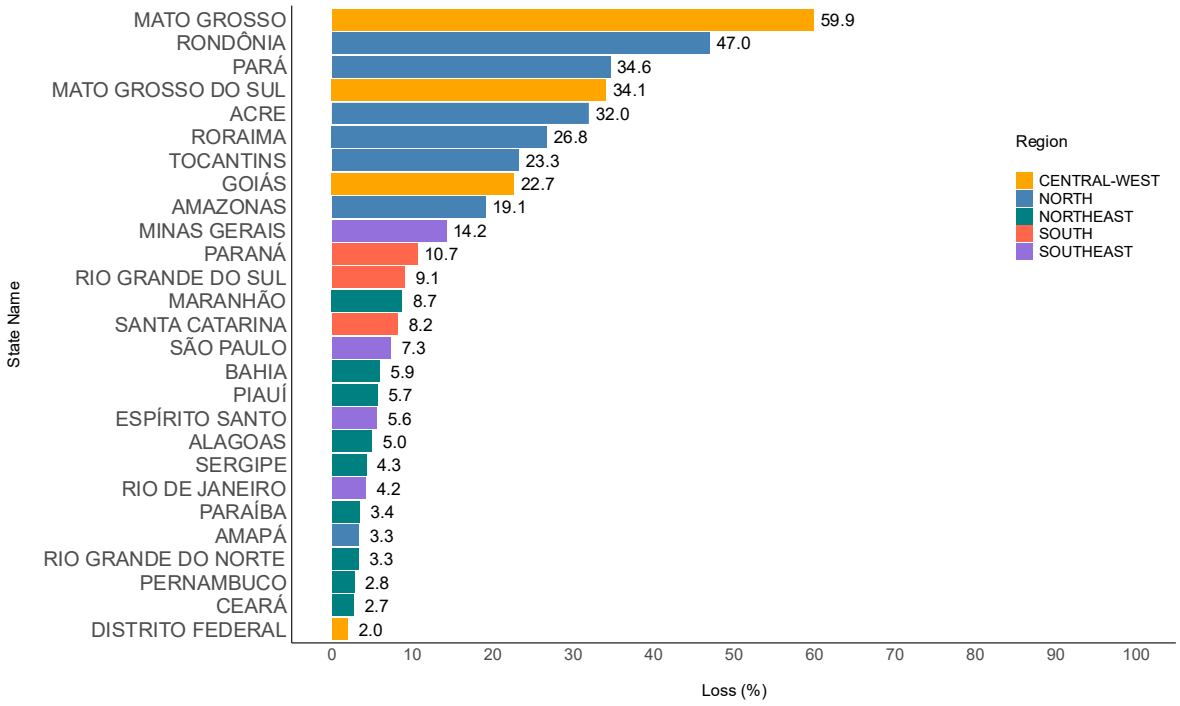


Source: UNDP-Brazil/FJP/Ipea and author's own calculations.

The percentage difference analysis reveals the magnitude of environmental costs embedded in different development models across Brazilian states. Mato Grosso experiences the highest percentage loss, with its PBHDI representing only 40.1% of its

original BHDI value, indicating that approximately 60% of its apparent human development comes at unsustainable environmental costs. Rondônia and Acre also experience substantial percentage losses, with reductions of approximately 47% and 32% respectively. These figures highlight the environmental unsustainability of development models prevalent in the Amazon region, where short-term economic gains often come at the expense of long-term ecological stability.

Figure 4: Percentage Differences between BHDI and PBHDI by State



Source: author's own calculations.

In contrast, several states demonstrate remarkable environmental efficiency. The Federal District and São Paulo experience minimal percentage losses (approximately 2% and 7% respectively), indicating that these states achieve high human development with relatively controlled environmental impacts. This efficiency likely results from their service-oriented economies, advanced infrastructure, and more stringent environmental regulations.

Discussion

The application of PHDI methodology to Brazilian states provides important insights for sustainable development theory and practice. The substantial ranking changes observed when environmental pressures are incorporated into development assessment demonstrate that traditional development metrics may provide misleading signals about the sustainability of development pathways. This finding supports growing calls for development approaches that explicitly account for environmental costs and planetary boundaries.

The analysis reveals that high human development performance, as measured by traditional indicators, does not necessarily correspond to sustainable development patterns. States like Mato Grosso achieve strong performance in health, education, and income dimensions while imposing substantial environmental costs that may undermine long-term sustainability. This pattern illustrates the fundamental tension between short-term development gains and long-term environmental sustainability that characterizes many contemporary development challenges.

Conversely, the improved performance of several Northeast states in PHDI rankings suggests that development models characterized by lower environmental pressures may offer pathways toward more sustainable development. While these states face challenges in traditional development indicators, their lower environmental impact demonstrates the potential for development approaches that operate within planetary boundaries while working toward human welfare improvements.

Methodological Contributions and Limitations

This study makes several methodological contributions to the application of planetary pressures-adjusted development metrics. The adaptation of PHDI methodology to the subnational level provides a framework for understanding regional development patterns and their environmental implications. The integration of comprehensive environmental data, including both greenhouse gas emissions and material footprint indicators, offers a more complete picture of environmental pressures than approaches that focus on single indicators.

The material footprint estimation methodology, while involving certain assumptions and approximations, represents the most comprehensive approach currently available for incorporating resource consumption patterns into subnational development assessment. The methodology builds on established techniques and utilizes the best available data sources to provide reasonable estimates of material consumption patterns across Brazilian states. This approach demonstrates the feasibility of extending planetary pressures assessment to subnational levels, despite data and methodological challenges.

The study also highlights important considerations for interpreting planetary pressures-adjusted development metrics. The relative nature of the normalization process means that rankings reflect comparative performance rather than absolute sustainability thresholds. This characteristic makes the PHDI particularly valuable for identifying regional patterns and comparative advantages in sustainable development, while acknowledging that additional analysis would be needed to assess absolute sustainability performance.

Policy Implications for Brazilian Development

The PHDI analysis provides several important policy implications for Brazilian development strategy. The poor performance of the Center-West region in adjusted rankings highlights the urgent need for sustainable agricultural policies that can maintain economic productivity while reducing environmental pressures. This

challenge requires integrated approaches that address both production practices and land use patterns, potentially including incentives for sustainable farming techniques, forest conservation, and restoration activities.

The improved performance of Northeast states suggests opportunities for development strategies that build on existing low-impact patterns while addressing traditional development challenges. These strategies might focus on service sector development, sustainable tourism, renewable energy, and other economic activities that can generate human welfare improvements with minimal environmental impact.

The analysis also reveals the importance of considering environmental efficiency in development planning. States that achieve high human development with relatively low environmental pressures demonstrate the potential for development models that operate within planetary boundaries. Understanding and replicating these patterns could inform sustainable development strategies for other regions facing similar challenges.

Conclusions

This study presents the first comprehensive application of Planetary Pressures-Adjusted Human Development Index methodology to Brazilian states, revealing significant insights into the relationship between human development and environmental sustainability across the country's diverse regions. The analysis demonstrates that incorporating environmental pressures into development assessment fundamentally alters our understanding of sustainable development patterns, with substantial implications for policy and planning.

The dramatic ranking transformations observed when environmental adjustments are applied underscore the environmental costs embedded in different development models. States like Mato Grosso, which achieve strong performance in traditional human development indicators, face substantial declines when environmental pressures are considered, highlighting the unsustainable nature of development patterns based on intensive resource extraction and high emissions activities. Conversely, several Northeast states demonstrate improved rankings when environmental factors are incorporated, suggesting development models that, while facing traditional development challenges, operate with greater environmental efficiency. These patterns indicate opportunities for sustainable development approaches that can achieve human welfare improvements while respecting planetary boundaries.

The study's methodological contributions include the successful adaptation of PHDI methodology to the subnational level and the integration of comprehensive environmental data encompassing both greenhouse gas emissions and material footprint indicators. The material footprint estimation approach, while involving certain methodological challenges, provides the most comprehensive framework currently available for incorporating resource consumption patterns into state-level development assessment.

The policy implications of this analysis are substantial. The poor performance of the Center-West region in adjusted rankings indicates an urgent need for sustainable agricultural policies and land use strategies that can maintain economic productivity while reducing environmental pressures. The improved performance of Northeast states suggests opportunities for development strategies that build on existing low-impact patterns while addressing traditional development challenges.

Future research should focus on extending this analysis to municipal levels, incorporating additional environmental indicators, and developing policy frameworks that can operationalize the insights from planetary pressures-adjusted development assessment. The methodology developed in this study provides a foundation for ongoing monitoring of sustainable development patterns and can inform evidence-based policy interventions aimed at achieving human welfare improvements within planetary boundaries.

The urgency of addressing climate change and environmental degradation makes the development of sustainable development metrics increasingly critical. This study demonstrates that such metrics can provide valuable insights for policy formulation and can help identify pathways toward development models that balance human welfare with environmental sustainability. As Brazil continues to play a crucial role in global environmental governance and sustainable development, the insights from this analysis can inform both national policy and international cooperation efforts aimed at achieving sustainable development within planetary boundaries.

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