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Ecosystem services provided by green areas and their implications for human health in Brazil

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ABSTRACT

Green areas provide numerous ecosystem services (ES) that are essential for human well-being, such as climate regulation, air quality regulation, disease regulation, and recreational opportunities. In this study, we assessed the ecosystem services provided by green areas and their implications for human health in Brazil. Considering emerging problems in Brazil, such as population growth, the health crisis, and the increase in deforestation, ES mapping is essential to understand barriers and diagnose strategies for promoting the health and well-being of the Brazilian population. Using remote sensing data and geographic information systems, we evaluated the Green Areas Ecosystem Services (GAES), composed of i) the provision of green areas; ii) regulation of air quality; iii) climate regulation; iv) diseases regulation (cardiorespiratory); and v) cultural services, including recreation, sports, and ecotourism. Our findings suggest that green areas in Brazil provide a considerable amount of ecosystem services that are relevant to human health. Over 70 % of Brazil exhibited GAES values exceeding 0.5 (relative scale ranging from 0 to 1). This indicates that a significant portion of the Brazilian population has access to green spaces that provide important services, such as air and water purification, climate regulation, and disease regulation. The mean GAES value for the entire country was 0.78, with notable regional variations. The highest GAES was found in regions dominated by the Amazon Forest (GAES = 0.81), while the smallest offers of GAES are in the northeast (GAES = 0.40) and south (GAES = 0.41) regions of the country The type of vegetation was an important factor in the regulation of climate and air quality. However, factors such as population density and urbanization interfere with the regulation of diseases. Considering the 10 states with the highest and lowest per capita income and population density, the state of Rio Grande do Sul, located in the South region, had the highest mean GAES value; while the state of Acre, in the North region, had the lowest. Our findings suggest that interventions to improve green area provision and quality may be most effective in the northeast and South regions of Brazil. This is indicative of the observed lower GAES provision in these regions, primarily attributed to elevated urbanization levels leading to the conversion of green areas into urban zones. Overall, our study highlights the importance of green areas for human well-being and provides valuable information for policy-makers to prioritize interventions to improve GAES provision across Brazil.

1. Introduction

Ecosystem services (ES) are the ecological characteristics, functions, or processes that directly or indirectly contribute to human well-being through various pathways (MEA, 2005). The ES approach transcends the simplistic view of nature as a passive backdrop to human existence; rather, it underscores nature's role as an active participant in shaping our health and quality of life. Changes in environmental processes can directly and indirectly influence human life in numerous ways. These influences can range from the most immediate and tangible, such as access to clean air and water, to the more subtle, yet equally vital, mediations, wherein alterations in the composition of species within each ecosystem ripple through the intricate network of life (MEA, 2005; Myers et al., 2013). It is within this intricate interplay between the

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environment and human well-being that the true essence of ecosystem services unfolds. Human benefits emanate from the integration of several categories of ecosystem services, each of which plays a pivotal role. The supporting services, serving as the foundational bedrock of all ecosystems, underpin the essential functions that sustain life on our planet. Regulating services, in their role as overseers of ecosystem processes, bestow a stable and hospitable environment. Provisioning services, in providing tangible products and resources, endow us with sustenance and sustenance-related products that are sourced from ecosystems. Finally, there is the cultural services, enriching human lives through aesthetics, recreation, and spiritual well-being (MEA, 2005).

Among the various components of an ecosystem, green spaces are of vital importance. Studies have shown that green areas in people's living environments have a positive association with the perceived general health of humans (Ali et al., 2022; Jabbar et al., 2022; Tzoulas et al., 2007; van den Berg et al., 2015). These spaces improve physical and mental health by mitigating environmental threats (e.g., air pollution, noise, microclimate dysregulation, and stormwater runoff), providing access to recreational opportunities, and facilitating social cohesion (Daniel et al., 2012; Ho Huu et al., 2018; Li et al., 2023; Liu et al., 2021; Muluneh and Worku, 2022). Green spaces have been shown to have a positive impact on mental health by reducing symptoms of anxiety, depression, and other mental health disorders (Ali et al., 2022). Additionally, green spaces have been linked to lower stress levels and improved cognitive function (Dadvand et al., 2015).

So far, multiple investigations on ES have been essential for the creation of the initial body of solid scientific evidence that has helped policymakers to create adaptive measures and mitigations. ES has been suggested as an essential approach for making decisions about social policies and land use management (Fu et al., 2021; Martinez-Harms et al., 2015; Rozas-Vásquez et al., 2019). The value of the ES in the development of policies and measures for society was recognized in the Sustainable Development Goals (SDGs), especially in SGD 2 (Zero Hunger), 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), and 11 (Sustainable Cities and Communities) (Hawken et al., 2021; Qiu et al., 2022; Yin et al., 2021). With the focus on SGD 3, governments, especially in the health sector, are making new efforts to embrace ES as an essential approach to help policymakers (Chiabai et al., 2018; Maes et al., 2016; McFarlane et al., 2019; Yin et al., 2021).

Although the growing body of ES studies in the last two decades, there is still a gap in the literature, given that most of the studies were performed in Europe and Asia with a focus on regulation services, mainly climate, water, and air pollution (Costanza et al., 2017; Evans et al., 2022). In Brazil, there are very few studies focused on ES (Pires de Souza et al., 2021; Teixeira et al., 2021; Urzedo et al., 2020). In a study by Parron et al. (2019), they identified 533 publications related to ecosystem services in Brazil up to 2017. Our extensive search, covering the period from 2018 to 2022, unveiled 1,331 studies in Brazil. Among these, 180 were centered on water regulation services (e.g., Nóbrega et al., 2020), 191 focused on climate regulation (e.g., De Carvalho and Szlafsztein, 2019), and 26 focused on disease regulation (e.g., Everard et al., 2020). To our knowledge, no study in Brazil has specifically focused on ES provided by green areas and ES related to human health. The existing research within Brazil primarily operates at a local or regional scale, limiting its broader applicability. To address this gap, our primary aim is the quantification and mapping of ecosystems in Brazil that are particularly relevant to human health.

Brazil faces a range of environmental challenges, including deforestation (da Silva et al., 2023), urbanization (Zeng et al., 2016), and climate change(da Veiga Lima and de Souza, 2022), which can have negative impacts on both the quantity and quality of green areas. Another important aspect to consider is that Brazil is a biodiversity hotspot, containing a large portion of the world's remaining tropical forests and a wealth of other unique ecosystems (Lagos and Muller, 2007). These ecosystems include the Amazon Rainforest, Cerrado savannas, Atlantic Rainforest, Pantanal wetlands, and the Caatinga biome. Each of these ecosystems possesses distinct flora and fauna, contributing to Brazil's exceptional biodiversity. These ecosystems provide numerous ecosystem services, including many that are crucial for human health and well-being. This study in Brazil will contribute with valuable insights to the international literature on the importance of green areas for human health, with particular emphasis on Brazil's unique ecological and cultural context. By providing a better understanding of the ecosystem services provided by green areas and their implications for human health in Brazil, this study can support policy decisions aimed at promoting the use and preservation of green areas, which could have far-reaching benefits for the health and well-being of the Brazilian population.

2. Materials and methods

This study followed the stepwise approach outlined by Burkhard et al., (2018) for mapping and assessing ecosystems and their services, consisting of eight steps. These steps included (1) theme identification, (2) identification, and mapping of the study area, (3) defining the study area condition and identifying the services provided by green areas, (4) selection of indicators for ecosystem condition and ecosystem services, (5) quantifying the indicators, (6) mapping the indicators, (7) integration of the results, and (8) dissemination and communication of the results (Fig. 1).

2.1. Theme identification (Stage 1)

In the initial stage of our methodology, we systematically identified and delineated the core themes pertinent to the ecosystem services offered by green areas and their implications for human health in the context of Brazil. We used comprehensive search terms and queries tailored to the specific dimensions of the study. The selection criteria for literature inclusion were based on relevance to the context of green areas and ecosystem services in Brazil, particularly focusing on their relationship with human health. To substantiate the identification of themes, we considered various sources, ranging from peer-reviewed scientific articles to government reports, guidelines, and initiatives pertinent to green areas and their ecosystem services.

Note that this first stage was structured to explore the multifaceted dimensions of this subject, including the health benefits associated with green areas, the diverse spectrum of ecosystem services provided by these areas, the prevailing state of green areas in Brazil, and the wide array of policies and initiatives devised to advocate for their utilization and conservation. This extensive exploration of the literature, which spanned a range of publication types, was instrumental in identifying and elucidating these key themes. This stage served as the foundation for subsequent stages in our methodology.

2.2. Identification and mapping of the study area (Stage 2)

Brazil, with a population of 210 million and an area of 8,516,000 km^2, offers a wide variety of habitats and ES that are strongly correlated with its different ecoregions, including the Amazon Forest, Atlantic Forest, Caatinga, Cerrado, Pantanal, and Pampas (Garcia et al., 2022; "IBGE," 2010; Tanure et al., 2020). These ecoregions or domains have distinct biotic, climatic, and geological features, such as the humid Amazon and Atlantic Forest, the Caatinga as a seasonally dry tropical forest, the Pampa as a dry temperate forest, the Pantanal as a wetland of fresh water and the Cerrado as a tropical savannah. Different types of ecosystems generate different types and intensities of ES. As Brazil has different ecoregions, which can be subdivided into different ecosystems, there is a wide variety of ES generated.

The study area encompasses different land uses/land cover, including forests, non-forest natural formations, agriculture and livestock, land without vegetation, and bodies of water ("Mapbiomas

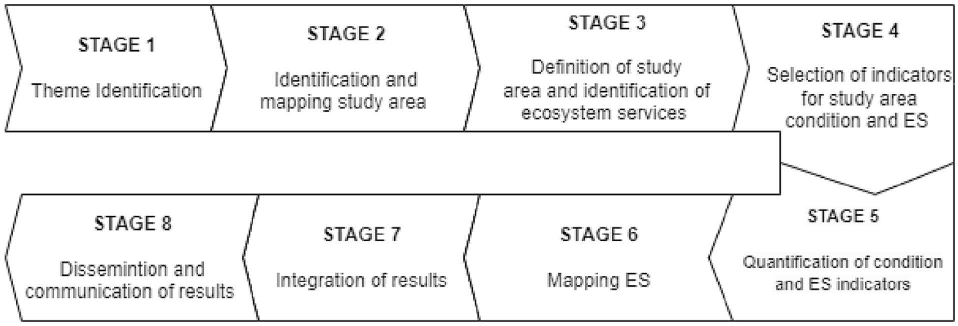

Fig. 1. Framework to evaluate the provision of ES. .
Source: Burkhard et al. (2018)

Brasil," 2023). Classes forests, non-natural formations, and agriculture and livestock correspond to 59.79 %, 6.34 %, and 31.15 % of the land use/cover, respectively. In total, approximately 97 % of the country is covered by green areas, being natural or non-natural vegetation (including agriculture), which offer differentiated ES. Despite this abundance of green areas, there are still significant disparities in the quality of health and healthcare across different populations, negatively influencing health/environment equity, and making it important to investigate the health benefits of green areas in Brazil.

2.3. Definition of study area condition and identification of ecosystem services delivered by green areas (Stage 3)

To define the study area condition and identify the ES delivered by green areas in Brazil, we conducted a thorough literature review. We selected the following ecosystem services provided by green areas in Brazil based on their relevance to human health and well-being:

(1) Green space provision: These are the benefits that are obtained from ecosystems. In the context of green areas and human health, provisioning services could include all benefits provides by green areas, that can be access by intermediaries ES as recreational opportunities and facilitating social cohesion, or contributing to improved physical and mental health. It is observed that general health of people living in greener areas tends to be better (Maas, 2006) and have been associated with reduced symptoms of anxiety, depression, and other mental health disorders (Ali et al., 2022).
(2) Air quality regulation: Vegetation in green areas absorbs pollutants such as carbon monoxide, nitrogen dioxide, sulphur dioxide, and tropospheric ozone through their leaves and converts them into oxygen and other harmless compounds (Ai et al., 2023; Diener and Mudu, 2021). Therefore, green areas play a crucial role in reducing air pollution and improving air quality, which is particularly important for urban areas in Brazil where air pollution is a significant problem (Castelhano et al., 2022). Cleaner air contributes to better respiratory health (e.g., reduce lung cancer and asthma incidence) and overall well-being (Danesh Yazdi et al., 2022; Requia et al., 2023);
(3) Climate regulation: Green areas reduce the temperature in urban areas, alter atmospheric circulation, and alleviate the urban heat island effect through transpiration, evaporation, and the absorption of solar radiation (Liu et al., 2021). This is particularly important in cities and other urban areas where the "urban heat island" effect can result in higher temperatures than in surrounding rural areas (Monteiro et al., 2021). By reducing temperatures in urban areas and mitigating the urban heat island effect, green areas help alleviate heat-related health issues that can be prevalent in cities, such as heat stress and heat-related illnesses (Wong et al., 2021). Cooler urban environments lead to improved comfort and well-being;
(4) Disease regulation: This includes the direct benefits to human health that are provided by ecosystems. In the context of green areas and human health, supporting human health could include the provision of opportunities for physical activity and social interaction, which can reduce the risk of chronic diseases and improve mental health (Yang et al., 2021). Note that the focus here is on the active contribution of green areas to disease prevention and well-being through specific activities, making a distinction from broader well-being and cultural aspects associated with other ecosystem services;
(5) Recreation, sports, and ecotourism: it is a cultural ecosystem service provided by green areas that contribute to human well-being by providing opportunities for physical activity, social interaction, and cultural and educational experiences (Nawrath et al., 2022; Zhu et al., 2023). Engaging in these activities enhances physical and mental health, thus positively impacting human well-being (Nawrath et al., 2022).

These services were chosen not only for their direct and indirect relevance to human health and well-being but also due to their capacity to inform critical policy and management decisions. Each of these ecosystem services has specific implications for policy-making and resource management. For example, green space provision is essential for urban planning and resource allocation, influencing policy decisions aimed at increasing the availability and quality of green spaces to enhance public health and community well-being. Air quality regulation, involving the role of green areas in reducing air pollution and improving air quality, is pivotal for urban and environmental policies, guiding strategies to preserve existing green spaces and establish new ones for mitigating air pollution-related health concerns. Understanding the impact of green areas on urban microclimates and temperature control is crucial for urban planning and climate adaptation policies, which promote the incorporation of green spaces into urban designs to create comfortable and sustainable urban environments. The availability of green areas offering opportunities for physical activity and social interaction influences public health programs and community well-being initiatives, shaping policy decisions aimed at fostering the creation and maintenance of such areas for disease prevention and overall well-being. Furthermore, recognizing the cultural ecosystem services provided by green areas, such as recreation, sports, and ecotourism, guides tourism and recreation policies, supporting local economies and enriching cultural and educational experiences for communities.

Note that these services can be grouped into three categories, including a provision (green spaces), regulation (air quality, climate regulation, diseases regulation), and cultural (recreation, sports, and ecotourism). Provisioning services are the products that are obtained from ecosystems, regulating services are the services that regulate environmental conditions, and cultural services are the non-material benefits that people obtain from ecosystems (MEA, 2005). Table 1 shows the groups of function and ecosystem services defined in our study.

2.4. Selection of indicators for the study area and ES selected (Stage 4)

To evaluate the provision of ecosystem services in Brazil, we selected 12 national-scale indicators based on several criteria. The indicators were chosen for their relevance to the provision of ecosystem services, availability of data at a national scale, quantifiability, reliability, and replicability (Albert et al., 2016; Burkhard and Maes, 2017).

For the ecosystem service represented by green space, the selected indicator was the Normalized Difference Vegetation Index (NDVI). This

Table 1
List of ES considering ecosystemic function, description, indicators, units used, and the font of the indicators used.

Function	Service	Description	Indicator	Units	Scale	Source	Literature	Relation with health	Relation with Green Areas
Provision	*******	Amount of green areas	NDVI*	NDVI	250 x 250 m	satellite image* processing	De Carvalho and Szlafsztein (2019)	The presence of green areas has a positive effect on health	–
		Cover and Use of Soil	Types of cover and use of soil	ha	30 x 30 km	image Landsat processing	Yang et al., 2022******	The presence of green areas has a positive effect on health	–
Regulation	Air quality regulation (Code CICES: 2.2.6.1)	Regulating/ improving air quality	$PM_{2.5}$	ug/m^3	10 x 10 km	satellite image processing*	Yang et al., 2022	High concentrations have a negative effect on health	The presence of green areas has a positive effect on the concentrations
			NO_2	ppb	10 x 10 km	satellite image processing*	Yang et al., 2022	High concentrations have a negative effect on health	The presence of green areas has a positive effect on the concentrations
			O_3	ppb	10 x 10 km		Yang et al., 2022	High concentrations have a negative effect on health	The presence of green areas has a positive effect on the concentrations
	Climate regulation (Code CICES: 2.2.6.2)	Regulating/ improving climate conditions	Temperature	°C	municipality	INPE***	Qiu et al., 2022	A certain range of values has a negative effect on health	The presence of green areas has a positive effect on the control of the range
			Relative humidity	%	municipality	INPE	Qiu et al., 2022	A certain range of values has a negative effect on health	The presence of green areas has a positive effect on the control of the range
	Disease regulation (Code CICES: 2.2.3.2)	Regulating/ improving health conditions	Incidence of respiratory hospital admissions	number of individuals	zip code	DATASUS****	Myers et al., 2013	–	The presence of green areas has a positive effect on the control of diseases
			Incidence of circulatory hospital admissions	number of individuals	zip code	DATASUS	Myers et al., 2013	–	The presence of green areas has a positive effect on the control of diseases
			Incidence of respiratory mortality	number of individuals	municipality	DATASUS	Myers et al., 2013	–	The presence of green areas has a positive effect on the control of diseases
			Incidence of circulatory mortality	number of individuals	municipality	DATASUS	Myers et al., 2013	–	The presence of green areas has a positive effect on the control of diseases
Cultural	Recreation, sport, and ecotourism (Code CICES: 3.1.1.1)	Recreation, sport, and ecotourism	Parks	Area (km^2)	regional	MMA*****	Venter et al., 2020	The presence of parks, *peri*-urban forests, and protected areas have a positive effect on health	The presence of parks, peri urban forest, and protected areas have a positive effect on health

* Normalized Difference Vegetation Index.
** Landsat 8 Image.
*** National Institute for Space Research.
**** Information Technology Department of the Brazilian Unified Health System.
***** Ministry of the Environment.
****** In this study was used a cover and use of soil, however, another methodology was used.
******* Green areas are categorized as intermediate services in accordance with CICES classification, representing their indirect contributions to ecosystem functions and human well-being.

indicator was chosen because it can provide an accurate measurement of vegetation greenness over time (Yang et al., 2021). Also was selected the indicator of land use. We accounted for the following categories of land use: Forest, representing Forest Formation, Savanna Formation, Mangrove, Floodable Forest and Wooded Sandbank Vegetation; Non Forest Natural Formation representing Wetland, Grassland, Hypersaline Tidal Flat, Rocky Outcrop, Herbaceous Sandbank Vegetation, Other non-Forest Formations; Farming representing Pasture, Forest Plantation, Agriculture of soybean, sugar cane, rice, cotton, coffee, citrus, palm oil and other crop; Non Vegetated Area representing beach, dune and sand spot, urban area and mining; and water. Fig. S1 shows a map with the land uses in Brazil and the better description of each class is shown in Table S1. This was chosen because it can help to identify the types of vegetation and land cover within green spaces, which can influence their quality and the services they provide (Hasan et al., 2020). Note that the green space provision service quantifies the availability and quality of green areas in the study area, considering factors such as the presence of green spaces and the type and quality of vegetation cover within these spaces. This service plays a crucial role in contributing to human well-being through aspects like access to recreational opportunities and fostering social cohesion.

For the ecosystem service represented by air quality, we selected three indicators: $PM_{2.5}$, NO_2, and O_3 concentrations (Chen et al., 2022; Yang et al., 2022). These indicators were chosen because they are known to be key pollutants that can have negative impacts on human health and the environment and can be quantified through national-scale satellite data (Kumar et al., 2019).

For the ecosystem service represented by climate regulation, we selected the indicators of temperature and relative humidity (Egoh et al., 2012). These indicators were chosen because they are key drivers of local and regional climate patterns, and can impact a variety of ecosystem services such as agriculture, water supply, and human health (Salmond et al., 2016).

For the ecosystem service represented by disease regulation, we selected the indicators as the incidence of hospital admissions and mortality rates for respiratory and circulatory diseases (Kondo et al., 2018; Schulz et al., 2018; Yang et al., 2021). These indicators were chosen because they can provide insights into the health impacts of environmental conditions, including the impacts of air pollution, climate conditions, and green spaces.

Finally, for the ecosystem service represented by recreation/sport/ecotourism, we selected the indicator of the presence of parks with accessibility and infrastructure for physical activity and ecotourism (Henke and Petropoulos, 2013). This was chosen because parks and other green spaces can provide a wide range of recreational and cultural opportunities for communities, including opportunities for exercise, socialization, and connection with nature (Nutsford et al., 2013).

Table 1 summarizes all the 12 indicators used in our study, including their sources, metrics, and spatial scale.

2.5. Quantification and mapping of indicators for the study area and ES selected (Stages 5 and 6)

To assess the provision of ecosystem services, we employed a matrix-based approach, combining Geographic Information Systems (GIS) and spreadsheet analysis. This methodology allowed us to calculate and spatially represent each indicator, producing maps of ecosystem service supply using standardized values that enable inter-regional comparisons or locally targeted assessments. Each indicator was assigned to suitable geo-biophysical spatial units by integrating relevant GIS layers and scored values, thereby generating ecosystem service provision maps across the study area (Lyu et al., 2023).

Given that each indicator has a specific dimension, we applied a standardization process similarly to Burkhard et al., (2012). Indicators were reclassified on scales ranging from 0 to 1, where 0 denotes a lack of potential for ecosystem service supply (minimum), and 1 indicates a very high relevance for ecosystem service supply (maximum). This standardization process ensured that each indicator was expressed in a consistent manner.

For example, for the ecosystem service of air quality regulation observing the WHO Air Quality Guidelines for the pollutants ($PM_{2.5}$, O_3, and NO_2) most of them are above AQG. For a better distribution and visualization of the data, we considered the higher the concentration of pollutants in the air, worse the air quality. In this case, we established a value of 0 for the maximum concentration of pollutants found in the data and established a value of 1 for the minimum concentration of pollutants found in the data. The intermediaries' concentrations vary according to the proportion of maximum and minimum following a linear regression. Where the value 0 is not relevant for this type of ES supply and 1 is relevant for this type of ES supply.

A similar approach was utilized for Diseases Regulation, where the indicators were established as 0 for the higher occurrences of hospital admission or mortality found in the data and were established as value 1 for the lower occurrences of hospital admission or mortality found in the data. Where the value 0 is not relevant for this type of ES supply and 1 is relevant for this type of ES supply.

For the Green space provision service, we used two indicators, including the presence of green spaces and the type of green spaces. For the first indicator, the presence of green spaces used the NDVI (Normalized Difference Vegetation Index). The NDVI ranges from -1 to $+1$. Negative values normally are associated with water. On the other hand, if you have an NDVI value close to 1, there is a high possibility that it's dense green leaves, and values close to zero, there are likely no green leaves and it could even be an urbanized area. Concurrently, the second indicator considered types of green areas based on land use classifications from Mapbiomas, adapted to the ecosystem service provision framework proposed by Burkhard et al. (2012). This adaptation allows us to comprehensively account for different land cover categories, including agricultural areas and natural forests, providing a nuanced understanding of the diverse ecosystem services delivered by distinct ecological landscapes. We use the land use classes considered in MapBiomas), and among the several classes, the classification that helps differs the green spaces was: i) Forest, representing forest formation, savanna formation, mangrove, and forest plantation; ii) Non-forest natural formation, representing wetland, grassland, salt flat, and other non-forest formations; iii) Farming, representing pasture, temporary crop, soybean, sugar cane, other temporary crops, perennial crop, and mosaic of agriculture and pasture; and iv) Non Vegetated Area, representing Beach, Dune and Sand Spot and Urban area. In Table S1, we present a description of each class. By considering these land use classes, we defined the value 0 for land use class that is no relevant to supply for the service and 1 for land use class that is maximum relevant supply for the service treated, being adapted from Burkhard et al. (2014) for Brazil landscape. For a better understanding on how the values of NDVI crossed with the land uses, we show in Figs. S2 and S3 land use maps and NDVI in Brazil. For Climate Regulation Services, we used temperature and relative humidity. The variation of these indicators was not high, so considered intervals and binaries values, 0 or 1. For temperature, values between 0 and 20 °C and above 26 °C were classified as 0, according to OMS temperatures in these intervals are prejudicial to human health. Temperatures between 20 and –26 °C are classified as 1 for being the ideal temperatures. For relative humidity, the interval classified as 1 was between 60 and 80 % and classified as 0 intervals between 0 and 60 % and above 80 %. Where 0 represents not relevant potential for ES supply (minimum) and 1 represents very high relevance for ES supply (maximum). We highlight that this simplification aimed to provide a clear representation of climate regulation services, acknowledging that a more intricate analysis of the nuanced interactions between temperature and humidity could be explored in future research.

A similar approach was utilized for Recreation, Sport, and Ecotourism Service, where a presence of parks or Conservation Units that provide opportunities for sports and outdoor activities was established at the value 1, and for parks that cannot possibility opportunities for sports and outdoor activities the value 0 was established. It is essential to note that this approach, while providing a straightforward representation, has inherent limitations. For example, it may not fully capture scenarios where natural settings like forests are used for recreation and sports without formal facilities, or urban or *peri*-urban areas, though smaller in scale (10 km), may possess dedicated facilities for sports and ecotourism.

All indicators were imported spatially into ArcGIS 10.7 for representation and analysis. When necessary, the indicators were resampled and aggregated to grids of 10 km resolution to facilitate their comparison.

2.6. Integration of results (Stage 7)

To integrate the results and analyze the data, a 10 km × 10 km grid was created over the study area. The potential supply of ecosystem services was calculated by equally weighting the indicators of each ecosystem service, as described in Equation 1

$$GAES = \{[(0.1\times \mathrm{NDVI}) + (0.1\times \mathrm{MAP}) + (0.1\times PM2.5) + ((0.1\times NO2) + (0.1\times O3) + (0.1\times TEMP) + (0.1\times HUM) + (0.1\times CARD_{HOSP}) + (0.1\times RESP_{HOSP}) + (0.1\times CARD_{MORT}) + (0.1\times RESP_{MORT}) + (0.1\times CU)\,]/1.2\,\}$$

Where GAES is the Green Areas Supply Ecosystem Services; NDVI represents the green Areas; MAP represents the quality of green areas (type of green spaces); $PM_{2.5}$ is the particulate matter less than 2.5 µm; NO_2 is the NO_2 concentration in the atmosphere; O_3 represents O_3 concentration in the atmosphere; TEMP means Temperature; HUM is Relative humidity; CARD_HOSP means Hospitalizations related to cardiovascular diseases; and RESP_HOSP represents Hospitalizations related to respiratory diseases; CARD_MOR is mortality related to cardiovascular diseases and RESP_MOR means Mortality related to respiratory diseases; and CU is Conservation Units.

Note we normalized the ES by including 0.1 as a constant. This enables different ecosystem services to be compared and evaluated at different points in time, allowing for the assessment of multiple ecosystem services simultaneously and the prevention of environmental degradation caused by low provisioning of ecosystem services.

We highlight that in the calculation of the GAES, we acknowledge the importance of accounting for the positive and negative impacts of ecosystem services on health effects. Environmental epidemiology recognizes the concept of thresholds, representing points at which exposure transitions from negligible to discernible health impacts. To incorporate this concept into our methodology, note that we employed a normalization process within the GAES equation. As we described before, this process involved assigning a value of 0 to the maximum concentration or maximum impact on health and a value of 1 to the minimum concentration or minimum impact on health. Intermediate concentrations follow a linear regression, ensuring a nuanced representation of the potential positive and negative impacts of ecosystem services on health. This approach allows for a more comprehensive evaluation, considering the varying thresholds at which different ecosystem services may affect human health. An illustrative example of this is the assessment of air quality regulation, where concentrations of pollutants are normalized based on WHO guidelines, with values closer to 1 indicating a maximum positive impact on health and values closer to 0 signifying a maximum negative impact. This normalization process is consistently applied across all ecosystem services, contributing to the reliability and robustness of our GAES calculations.

The analysis was across different regions in Brazil, so the results were focused on each country region (North, Northeast, Midwest, Southeast, and South), as illustrated in Fig. 4, and for better understanding the variation of GAES values was highlighted 10 states. The criteria used to choose the states were the highest and lowest: Gross Domestic Product (GDP) and population. These criteria can represent economic and social factors in this study, to maybe link with some environmental problems such as deforestation, urbanization, and environmental disasters. The states with a smaller population and GDP were Roraima, Amapá, Acre, Tocantins, and Rondônia; and the states with the biggest population and GDP were São Paulo, Rio de Janeiro, Minas Gerais, Rio Grande do Sul, and Bahia as shown in Fig. 4.

Finally, a sensitivity analysis was performed. This technique consists of a method to describe how much a change in the values of a set of variables affects other variables under certain conditions (Foody et al., 2016). In more general terms it measures the robustness associated with the resulting output with manipulated input variables. To investigate the sensitivity of each ES was weighted to data dimensionality. The weight was distributed where each ES at a time was weight with 50 %, and the others 50 % was equivalent distributed of others ES.

3. Results

Table 2 shows the descriptive statistics of Green Areas Supplying Ecosystem Services (GAES) in Brazil (as mentioned before, GAES values are ranked on a relative scale from 0 to 1). The results indicate that the mean GAES value for Brazil as a whole was 0.78, with a standard deviation of 0.08, a minimum value of 0.40, and a maximum value of 1.0. The regional analysis reveals some variations in the GAES values across different regions. For example, the mean GAES value was 0.77 in the Midwest region, 0.75 in the Northeast, 0.81 in the North, 0.76 in the Southeast, and 0.70 in the South.

To further explore the variation of GAES values across different regions, we generated box plots for the GAES values in each region (Fig. 2) and the for the most populated and rich states, as well as, the less populated and poor states (Fig. 3). The distribution of GAES values within each region reveals that the North region had the highest median value of GAES, while the South region had the lowest median value. The box plots also show some outliers indicating regions of particularly high (e.g., North) or low (e.g., Midwest) GAES values (Fig. 2). Also was observed that few outliers above maximum values (e.g., Midwest, Southeast, and South). In the boxplots for the 10 states (Fig. 3), we can observe that the state of São Paulo showed significant outliners for high and low, and the states of Acre, Amapa, Minas Gerais e Rondônia also show high and low outliners in minor quantities. The States of Bahia, Tocatins and Rio Grande do Sul has outliners below the minimum. The states of Rio de Janeiro and Roraima did not show outliners. These states have a more uniform distribution of GAES. In others, States can be variations related to different services, such as climate regulation or quality of green areas.

Fig. 3 shows the states from the north region, as Tocatins (TO) and Rondonia (RO) have the best distribution of ES supply, with most of the values above 0.8 and few outliners. Acre (AC) showed average values (0.7) and diverse outliners. Another state that presents values lower than 0.7 is Rio Grande do Sul (RS), where the minimum is 0.52. The other analysed states show average values between 0.7 and 0.8, with similar distribution, except for the state of Bahia, with a greater distribution of values close to 0.7, and the state of São Paulo with a smaller distribution and a greater number of outliers.

Fig. 4 shows the map of GAES in Brazil. The map highlights the spatial distribution of the GAES values across Brazil and reveals that the highest values are mainly concentrated in the northern and central-western regions of the country. More than 70 % of Brazil has GAES values above 0.5, with maximum values found in the north, coinciding with the presence of part of the Amazon Forest domain, and other areas such as portions of the northeast, with the presence of the Caatinga domain, and the south coast of São Paulo, presence of the Atlantic Forest domain. In contrast, the minimum and intermediate values were found in Acre (AC) state in the northern region; in the countryside of the northeast; and in southern regions, as well as in Mato Grosso do Sul

Table 2
Descriptive statistics of GAES in Brazil. The results are also presented by regions and for 10 select states, the 5 states richer and more populated and 5 states less rich and populated.

Local	Minimum	Quartile 1	Mean	Standard deviation	Quartile 3	Maximum
Brazil	0,40	0,72	0,78	0,08	0,84	1,00
Region						
Midwest	0,49	0,72	0,77	0,07	0,82	0,98
Northeast	0,40	0,69	0,75	0,08	0,81	0,95
North	0,44	0,76	0,81	0,08	0,87	1,03
Southeast	0,51	0,72	0,76	0,06	0,82	0,98
South	0,42	0,66	0,70	0,07	0,76	0,92
States						
Acre	0,44	0,67	0,69	0,07	0,44	0,85
Amapa	0,58	0,58	0,77	0,05	0,82	0,94
Bahia	0,47	0,47	0,77	0,07	0,82	0,94
Minas Gerais	0,54	0,54	0,77	0,06	0,47	0,94
Rio de Janeiro	0,54	0,73	0,77	0,06	0,82	0,97
Roraima	0,58	0,71	0,76	0,07	0,81	0,96
Rondonia	0,60	0,60	0,77	0,06	0,81	0,94
Rio Grande do Sul	0,67	0,80	0,83	0,05	0,86	0,96
São Paulo	0,42	0,67	0,71	0,07	0,77	0,89
Tocatins	0,51	0,71	0,75	0,07	0,79	0,98

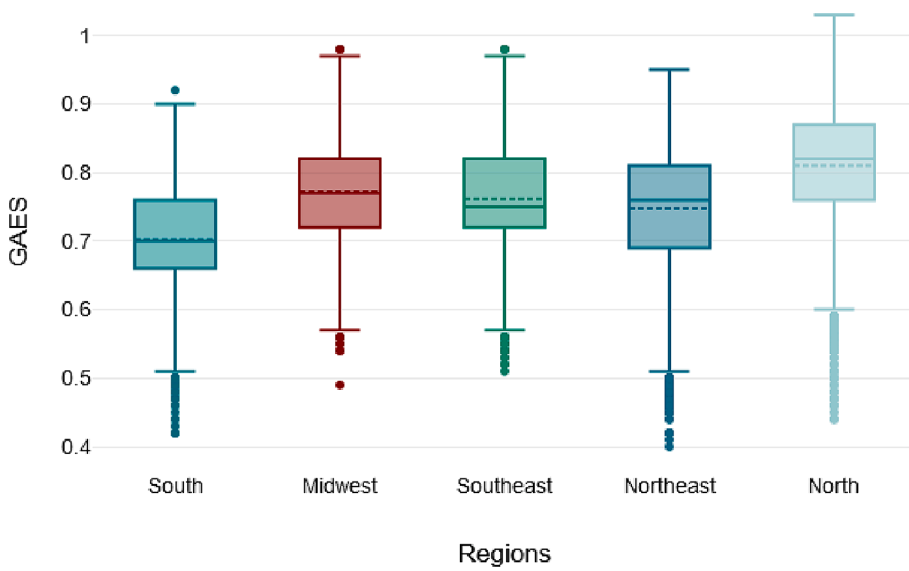

Fig. 2. Boxplot of ES supply by Brazilian regions.

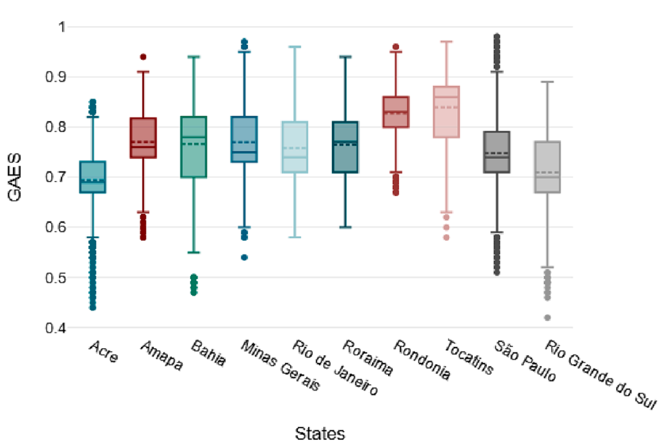

Fig. 3. Boxplot of ES supply in the 10 selected states in Brazil, the 5 states richer and more populated and 5 states less rich and populated.

(MS). Fig. 4 illustrates that the two most “disadvantaged” areas, in terms of GAES, are in the countryside of northeast Brazil, possibly related to the absence of green areas and climate anomalies. The South region, specifically in the state of Santa Catarina (SC), and the North region, specifically in Acre (AC), showed the same pattern.

Fig. 5 shows the sensitivity analysis for each ES and shows that there are relevant differences between each ES result. Each shows a different pattern, but all ES shows a higher value in the northern states. The green tones indicate areas where the “positive” provision of the factors is high, which means, for example, a high provision of recreation, sport, and ecotourism opportunities or a low rate of people who have a cardiovascular illness. The red and orange tones represent the “negative” or absence of provision of the service, such as a high concentration of pollutants in the air or high temperatures that interfere with human well-being.

4. Discussion

Our findings suggest that green areas in Brazil provide a considerable amount of ecosystem services that are relevant to human health. The ES supply map (Fig. 4) revealed substantial spatial variability, with more

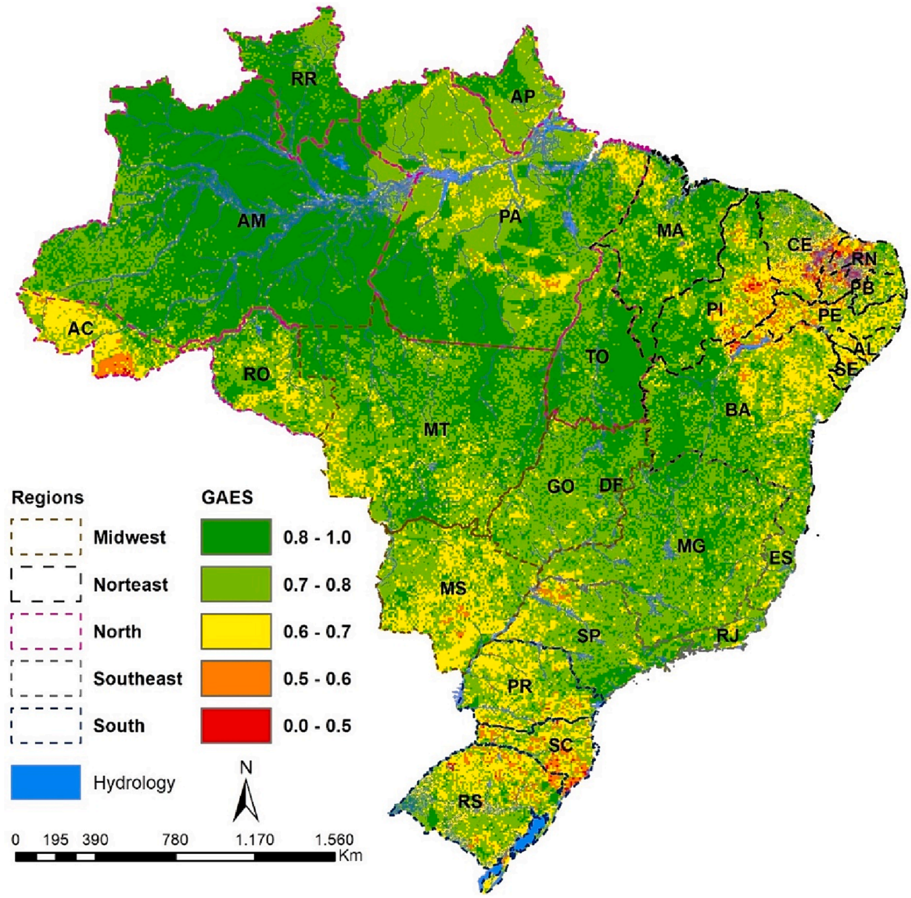

Fig. 4. Provision level map of ES supply by green areas. Note 1: GAES scales ranging from 0 to 1, where 0 represents a non-relevant potential for ES provision (minimum) and 1 represents very high relevance for ES provision (maximum). Note 2: Acre (AC); Alagoas (AL); Amapá (AP); Amazonas (AM); Bahia (BA); Ceará (CE); Distrito Federal (DF); Espírito Santo (ES); Goiás (GO); Maranhão (MA); Mato Grosso (MT); Mato Grosso do Sul (MS); Minas Gerais (MG); Pará (PA); Paraíba (PB); Paraná (PR); Pernambuco (PE); Piauí (PI); Roraima (RR); Rondônia (RO); Rio de Janeiro (RJ); Rio Grande do Norte (RN); Rio Grande do Sul (RS); Santa Catarina (SC); São Paulo (SP); Sergipe (SE); Tocantins (TO). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

than 70 % of Brazil having a GAES provision above 0.5. This indicates that a significant portion of the Brazilian population has access to green spaces that provide important services, such as air and water purification, climate regulation, and disease regulation.

However, our findings also highlight disparities in GAES provision across different regions of the country, which could have important implications for policy and management strategies aimed at preserving and enhancing ecosystem services in Brazil. The highest values of ecosystem service provision were found in areas of the Amazon Forest, especially in the northwest portion of the northern region. In contrast, the northeast and south regions had the lowest mean GAES provision, with some areas showing GAES provision as low as 0.4. The finding that the Amazon Forest has the highest values of ecosystem service provision is not surprising given the vast size and biodiversity of this region (Ferreira and Féres, 2020). The Amazon Forest is known to be a critical contributor to the regulation of global climate and hydrology, in addition to supporting local communities and biodiversity (Heinrich, 2009; Tanure et al., 2020). On the other hand, the low GAES provision found in the Northeast and Southern regions can be explained by several factors. First, the South region has less coverage of green areas compared to other regions of Brazil. And the Northeast region has specific climatic anomalies (Costa et al., 2020) that affect the ability of green areas to provide ecosystem services. For example, the northeast region has, mainly in the interior part of the state, a semi-arid climate (Bsh) characterized as very hot and seasonally dry with irregular distribution of rainfall in short periods of the year (Ab'Saber, 2003) that will limit water availability, make reflectance and evapotranspiration high, reducing the ability of green areas to regulate climate and provide other ecosystem services. These findings suggest that there is a need for targeted efforts to increase the coverage and quality of green areas in the northeast and south regions, to improve the provision of ecosystem services and ultimately benefit human health and well-being. It is important to note that the provision of ecosystem services is not only influenced by the number of green areas but also by their quality and spatial configuration. Therefore, conservation and restoration efforts should aim to enhance the connectivity and functionality of green areas in these regions.

Of the 7 theses states that were selected 5 states from regions north - Acre, Amapá, Roraima, Rondônia, and Tocantins - theses states are the less populated and most poor. Despite presenting similar socioeconomic conditions concerning the GAES, a difference is observed. The states of Tocantins and Rondônia have higher values and few outliners, possibly associated with the lack of climatic anomalies and the presence of parks. The state of Acre has a climatic anomaly and a lower vegetation cover, possibly related to outliners with values between 0.4 and 0.58. The state of Amapá also has outliners below the lower limit, which, as mentioned in the previous case related to climate variation, is an outliner above the upper limit. However, comparing Amapá and Acre, the former has greater vegetation cover and the disease regulation service is more positive. The state of Roraima does not have outliners and has greater vegetation cover and air quality, and disease regulation services are more positive. positive GAES values and the absence of outliners show a

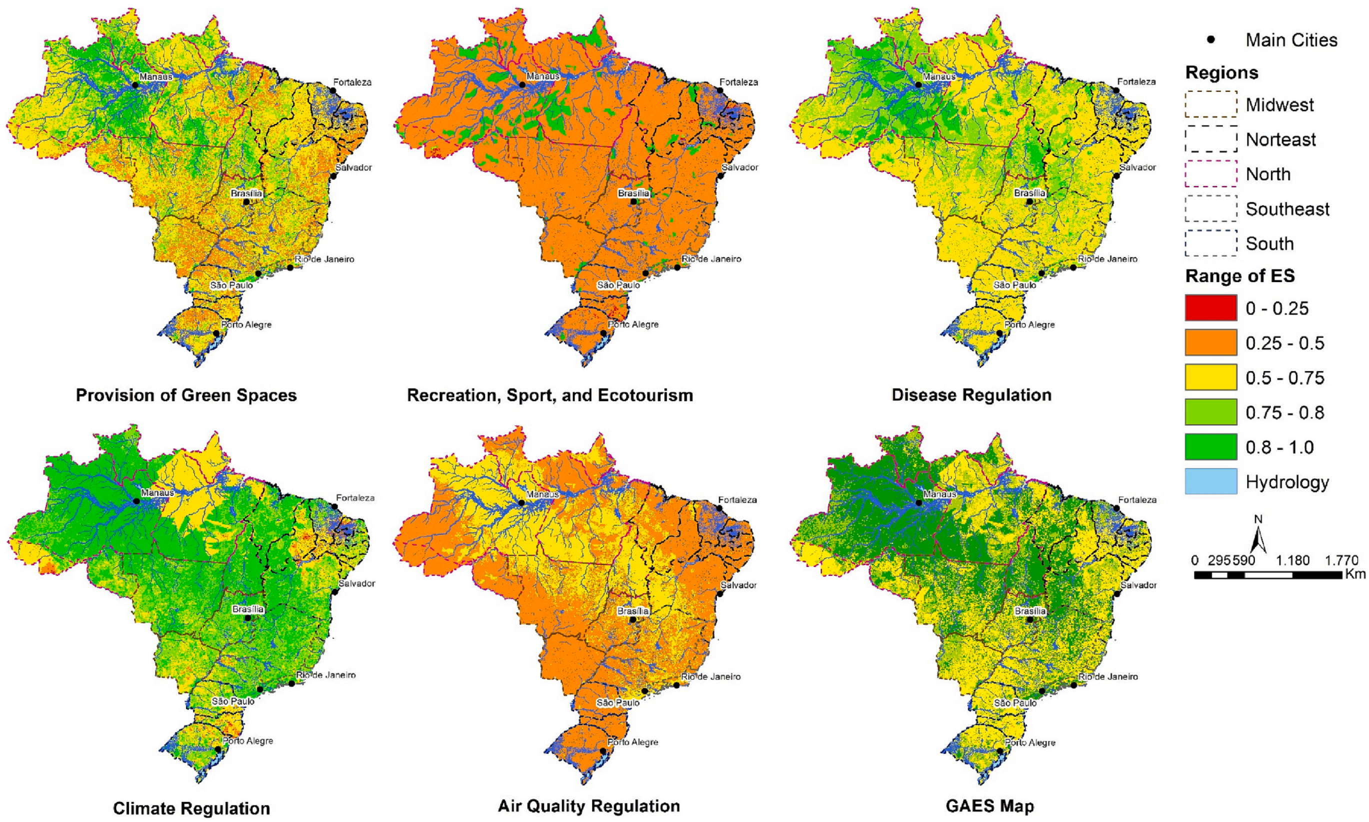

Fig. 5. Sensitivity analysis for each ES analysed. Each ES was highlighting, and last map is the GAES map (Fig. 4), result of the 5 ES analysed. Note 1: GAES scales ranging from 0 to 1, where 0 represents a non-relevant potential for SE provision (minimum) and 1 represents very high relevance for SE provision (maximum). Note 2: Acre (AC); Alagoas (AL); Amapá (AP); Amazonas (AM); Bahia (BA); Ceará (CE); Distrito Federal (DF); Espírito Santo (ES); Goiás (GO); Maranhão (MA); Mato Grosso (MT); Mato Grosso do Sul (MS); Minas Gerais (MG); Pará (PA); Paraíba (PB); Paraná (PR); Pernambuco (PE); Piauí (PI); Roraima (RR); Rondônia (RO); Rio de Janeiro (RJ); Rio Grande do Norte (RN); Rio Grande do Sul (RS); Santa Catarina (SC); São Paulo (SP); Sergipe (SE); Tocantins (TO).

homogenization of values and no anomalies.

Of the 4 states in the southeast, 3 states were selected, Rio de Janeiro, São Paulo, and Minas Gerais, which represent the richest and most populous states in the country. The three states have a wide distribution of GAES values with similar means. The state of São Paulo has greater disparities and outliners, a lower concentration of vegetation cover is observed in the west of the state related to agriculture and livestock, and a worse service of air quality related to intense urbanization in the coastal region of the state (Yu et al., 2023). Rio de Janeiro has portions of preserved Atlantic Forest and for geographical reasons linked to atmospheric currents, the air quality is better. This is similar to the state of Minas Gerais, which has better air quality and climate regulation service but still lacks vegetation cover.

The Rio Grande do Sul is a state of South region, it is a state among the most populous and with the highest GDP. It has the lowest GAES values followed by several outliners below the lower limit, which can be selected for lack of vegetation cover and climate anomalies. Despite having an average above 0.7, a portion with values of 0.4 is worrisome, and it is necessary to verify, in addition to the type of land use and cover, other factors that corroborate this value, such as a possible lack of health treatments or the type of vegetation installed or infrastructure for the practice of sports (Liu et al., 2023).

The state of Bahia is one of the most populous and with the highest GDP in the northeast. The lack of robust vegetation cover and the replacement of native vegetation by agriculture on the banks of the São Francisco River does not seem to be substantial for services once GAES values exceed 0.8. Air quality and disease regulatory services seem to deteriorate further west, past the Borborema plateau. The trade winds and the high-pressure system combined with the natural physical obstacle of the Borborema plateau contribute to climate anomalies. And it affects the circulation of goods and services as the disease regulation service worsens in these regions.

Local case studies highlight Brazil's potential as a provider of various ecosystem services, in addition to the structures and infrastructure already in place for this. Ocelli Pinheiro et al., (2021) highlight the role of Marine Protected Areas in the provision of cultural ecosystem services. Resende et al., (2021) show the importance of parks for ecosystem maintenance regulation services. Nóbrega et al., (2020) show the impact of replacing natural vegetation with agriculture and livestock in water quality regulation services. Parron et al., (2022) show a significant demand for changes in land use and management to deliver improved ES provision in the agricultural landscapes in Parana state. As well, Schuler et al., (2022) said that agroforestry affects water provision and regulation and they should be replaced with a more sustainable option. All these are study cases that detail aspects of each region, but all show the importance of green cover for the provision of ecosystem services.

To provide a more insightful and meaningful interpretation of the results, we discuss our findings below according to the five categories of ecosystem services analysed in this study: green space provision, air quality regulation, climate regulation, disease regulation, and recreation/sports/ecotourism. Each category represents a different aspect of the relationship between green areas and human health and discussing them separately enables a deeper exploration of the nuances within each category. Additionally, this stratified discussion facilitates the identification of areas where ecosystem services are particularly strong or weak, and where interventions may be most effective in improving human health outcomes.

4.1. Green space provision

The regional variations in GAES provision observed in this study underscore the importance of discriminating between different ecosystems and land uses to elucidate their distinct implications for human health. Our study found that the northern region of the Amazon Forest domain had the highest green space provision, while the Southeast and South regions had the lowest provision. This could be related to the high levels of urbanization in these regions, which has led to the removal of natural vegetation and the conversion of green areas into urbanized zones (Hou et al., 2023; Ludermir and Harpham, 1998).

The provision of green spaces is important for improving human health outcomes, as it provides opportunities for physical activity and recreation, reduces stress levels, and promotes mental health(Nguyen et al., 2021; Yang et al., 2021). It also contributes to the overall aesthetic and ecological value of a region (Wang et al., 2019).

The quality of green spaces encompasses the characteristics of the green areas themselves, such as size, shape, biodiversity, and accessibility. Our results indicate that the quality of green spaces is an important factor in the provision of ecosystem services. For example, larger and more diverse green spaces tend to provide greater benefits in terms of air and water quality, as well as habitat for wildlife (Coutts and Hahn, 2015; Salmond et al., 2016; Tzoulas et al., 2007). Similarly, green spaces that are easily accessible to the public tend to have greater human well-being benefits, as they can be used for recreation and relaxation (Pröbstl-Haider, 2015; Venter et al., 2020).

Expanding our focus beyond forested areas, the role of various land use classes becomes apparent. Agricultural areas, often characterized by extensive crop cover and reduced natural vegetation, pose unique challenges and opportunities for GAES provision. While they contribute to provisioning services, such as food production, the associated reduction in green spaces may limit certain ecosystem services crucial for human health, such as recreational opportunities and stress reduction.

Similarly, industrial areas may exert additional pressures on GAES provision. The altered landscape, pollution, and reduced green spaces in these zones can have adverse effects on human health. Understanding the differential impact of diverse land use classes on GAES provision allows for more targeted and effective interventions. Incorporating such nuanced insights into urban planning and policy decisions is essential to balance economic activities with the preservation and enhancement of green areas, ensuring optimal GAES provision for improved public health across various landscapes.

Interventions aimed at increasing green space provision in urban areas can have significant impacts on human health outcomes, especially in areas with high population density and limited access to green areas. These interventions may include the creation of urban parks, green roofs, community gardens, and green corridors (Krsnik et al., 2023; Nawrath et al., 2022). Our results suggest that efforts should be made to improve the quality of green spaces in regions with low GAES provision. This may involve planting more diverse vegetation, increasing the size of existing green spaces, or improving access to green spaces through the creation of new parks and greenways.

4.2. Air quality regulation

Our results indicate a consistent pattern wherein regions with higher green area provision tend to exhibit improved air quality indicators, especially in the North and Southeast regions. This is particularly important in urban areas, where air pollution is a major public health concern (WHO, 2021). The presence of green areas can help to mitigate the negative impacts of air pollution on human health, as well as provide recreational and aesthetic benefits (Kruize et al., 2019). Green areas have been shown to play a significant role in mitigating the negative impacts of air pollution on human health by reducing the concentrations of pollutants such as particulate matter and nitrogen oxides in the air (Kumar et al., 2019). This is because vegetation acts as a natural filter, trapping and absorbing pollutants as air passes through it (Wang et al., 2014). This way the region north with the biggest vegetal cover has better air. However geographic factors such as the Borborema Planalto, the presence of vegetation is essential for the regulation of air quality, as seen in Fig. 4, the air quality service follows a pattern similar to the provision of green areas as observed in the state of Amapá or São Paulo. But in addition to the green areas, geographical factors such as orogenic obstacles, such as the Borborema plateau, or atmospheric cells, high-pressure cells in the state of Maranhão, act in the management and transport of pollutants. It is important to note, however, that not all green areas are equally effective in providing air quality benefits. Our study also assessed the quality of green spaces (as discussed above), which can impact their ability to provide air quality benefits(Jabbar et al., 2022). For example, well-maintained green spaces with a variety of vegetation types may be more effective at mitigating air pollution than poorly maintained green spaces with limited vegetation (Bhandari and Zhang, 2022). Additionally, the proximity of green spaces to sources of air pollution, such as highways and industrial facilities, can impact their effectiveness in providing air quality benefits (Akaraci et al., 2022).

Overall, our findings highlight the importance of considering the role of green areas in improving air quality as a public health strategy, particularly in urban areas. By promoting the development and maintenance of green areas, policymakers can not only improve air quality but also promote the well-being and quality of life of local communities.

4.3. Climate regulation

Climate regulation is one of the most essential ecosystem services provided by green areas (De Carvalho and Szlafsztein, 2019; Guillen-Cruz et al., 2021), as they play a crucial role in regulating the local climate. Green areas absorb carbon dioxide (CO_2) from the atmosphere and release oxygen through photosynthesis, thus acting as carbon sinks that help to mitigate the effects of climate change (Wang et al., 2014). Our results support the indication that the presence of green areas is vital for regulating the local climate, especially in regions where the natural vegetation has been removed (De Carvalho and Szlafsztein, 2019). In addition to absorbing carbon, green areas also provide cooling through the process of evapotranspiration, which helps to reduce the urban heat island effect and provides relief during heat waves (Ellison et al., 2017).

It is important to highlight the role of the Amazon Forest in regulating the global climate (Baker and Spracklen, 2019). However, our results also indicate that deforestation in this region has a severe impact on the global climate system. The area of Amazon Forest according to our data corresponds the mean of GAES is 0.8, in contrast, the area of natural vegetation is being replaced by agriculture, grazing, or mining which corresponds to 0.56 of GAES. So, it is possible to verify the difference generated in the provision of services related to climate regulation generated by natural vegetation and the Amazon rainforest. It is, therefore, essential to prioritize conservation efforts in the Amazon Forest to ensure its continued ability to regulate the climate providing significant ecosystem services. On the other hand, when this difference between unnatural vegetation and the caatinga biome is verified, it is observed that the plantations demonstrate a positive balance, bringing more benefits in terms of climate.

We can observe disparity between the provisioning of air quality and climate regulation. While both services are expected to be influenced by similar ecosystem characteristics, such as natural forests or rivers, several factors may contribute to the observed variations(Qiu et al., 2023). First, it is crucial to note that the relationship between air quality and weather parameters, such as temperature and humidity, is often complex and non-linear. While our study considered broad indicators for climate regulation, the intricate interplay between air pollutants (such as PM2.5, NO2, and O3) and weather conditions can lead to variations that are not fully captured by these broad indicators. Future research could delve into more specific indicators related to air quality and meteorological parameters, allowing for a more nuanced understanding of their interactions. Second, the seemingly high climate regulation service across much of the country could be influenced by the predominantly tropical climate, with temperatures and humidity falling within the ideal range for this ecosystem service. However, the effectiveness of natural ecosystems in regulating air quality may be influenced by additional factors, including the concentration and types of pollutants, atmospheric conditions, and land-use patterns. Finally, localized sources of pollution, industrial activities, and urbanization could contribute to the observed disparities in air quality provisioning. While our analysis provides a broad-scale overview, it may not fully capture the localized dynamics of air quality challenges.

4.4. Disease regulation

While our study suggests a potential association between the incidence of diseases and the geographical distribution of green areas, it's essential to acknowledge the speculative nature of this discussion. Our findings indicate a higher incidence of diseases in the Southeast and South regions of Brazil, which may be attributed to factors such as higher population density and increased urbanization. Exposure to disease vectors and limited access to green areas could contribute to this pattern (Everard et al., 2020).

While our results hint at the importance of green areas for potential disease regulation and human health, we recognize the need for caution in drawing firm conclusions without dedicated correlation analyses. As urbanization expands and natural habitats face threats, there is a growing imperative to understand and safeguard the role of green areas in supporting human well-being. Further research employing rigorous methodologies is warranted to delve into the intricate relationships between green areas and disease regulation.

4.5. Recreation, sports, and ecotourism

The provision of recreational opportunities can have important social and economic benefits, such as promoting physical activity, reducing stress, and supporting local tourism industries (Nawrath et al., 2022). The presence of green areas can also provide opportunities for sports and outdoor activities, which can promote healthy lifestyles and enhance community well-being (Ocelli Pinheiro et al., 2021). Ecotourism, in particular, can provide economic benefits for local communities while also promoting the conservation and sustainable use of natural resources (Kiper, 2013; Samal and Dash, 2023).

Our study found that the highest provision of these services was in the Amazon Forest, which has great potential for ecotourism and other recreational activities. However, the southeast and south regions of Brazil, which had the lowest provision of green areas, also had low provision of these services. In areas with low GAES provision in this category, such as in the Northeast and South regions, increasing access to green spaces for recreational activities and ecotourism could have positive impacts on physical and mental health outcomes.

Note that we used the presence of parks and Conservation Units as indicators for recreation, sports, and ecotourism. While this approach allowed us to capture the potential for sports and outdoor activities in natural settings, it may not fully represent urban or *peri*-urban parks equipped with facilities for various recreational activities. The discrepancy, highlighted in Fig. 5, may be attributed to the scale of our analysis (10 km) and the specific indicators used. The term 'Recreation, Sports, and Ecotourism Service' in our study primarily focused on the natural and protected areas that inherently support these activities. However, we acknowledge that urban or *peri*-urban areas with dedicated facilities for sports, trails, bike paths, and other recreational amenities may not have been comprehensively captured at this scale. In retrospect, a more nuanced categorization or inclusion of additional indicators reflecting the infrastructure for recreational activities in both natural and urban settings could refine the accuracy of our results. This limitation should be considered in future studies, emphasizing the need to tailor indicators to the diverse nature of recreational activities across different landscapes.

4.6. Limitations, strengths, and future research directions

Our study has several limitations. First, we did not consider the socioeconomic and demographic characteristics of the population living in each region and state. Therefore, the GAES provision may be influenced by factors such as income, education, and cultural differences, which were not considered in this study. These factors are potential confounders that could influence the observed health indicators. Second, we accounted for equal weight for each service. This means that, for example, areas with larger green spaces may have been given the same importance as areas with smaller green spaces but with higher quality. Further studies should address this issue by incorporating in the study design an approach to individualize the weight (e.g., a multicriteria model). Third, the data used in this study were collected from secondary sources and may not reflect the current situation in each region. Additionally, some data may have been missing or incomplete, which could have affected the accuracy of the results. Furthermore, the dependence of our results on the chosen methodology should be acknowledged, and it is important to note that there are alternative methods, including the SEEA-EA proposed by the U.N. (https://seea.un.org/). Another limitation is related to the oversimplification in our calculation of ecosystem services supply, particularly regarding specific indicators, air pollution. While we considered a range of ecosystem services provided by green areas, it's important to note that not all species contribute equally to air depuration. Studies such as Muresan et al. (2022) have shown variability in the capacity of different species to remove air pollutants, highlighting the need for more nuanced assessments in future research (Muresan et al., 2022). However, it is essential to consider the challenges in Brazil's diverse landscapes. Simplified indicators, chosen for broad relevance, enable consistent evaluation, facilitating cross-service comparisons. While a limitation, this deliberate choice enhances reliability for large-scale insights. Finally, the study only analysed GAES provision in Brazil and may not apply to other regions or countries with different ecological, cultural, and social characteristics or levels of urbanization. Therefore, caution should be taken when generalizing the results to other regions or countries.

Despite the limitations, our study has some strengths. First, this was a comprehensive analysis by considering multiple categories of ecosystem services provided by green areas. Second, we used a robust methodology. The GAES index used in this study is a validated and widely-used methodology for assessing the provision of ecosystem services by green areas (Hattam et al., 2021; Maes et al., 2016). Third, the study covers a large geographical area, providing insights into the provision of ecosystem services in different regions of Brazil. Finally, this study adds to the growing body of literature on the importance of green areas for ecosystem service provision and their relationship with human well-being and health, particularly in urban settings.

In addition to the limitations and strengths outlined above, further discussion for future research merit thorough consideration. First, exploring the nuanced contributions of different plant species to ecosystem services, particularly air depuration, would enhance our understanding of the effectiveness of green areas in mitigating air pollution. Future studies could focus on the specific mechanisms by which various species influence air quality, providing valuable insights for urban planning and green infrastructure management. Second, there is a growing need for research that integrates socioeconomic and demographic factors into the assessment of ecosystem services provision. Understanding how factors such as income, education, and cultural differences interact with green areas' benefits can inform more equitable and effective strategies for enhancing human well-being through nature-based solutions. Furthermore, developing sophisticated modeling approaches that consider not only the quantity but also the quality of green spaces could refine our assessments of ecosystem services. Incorporating data on green space size, vegetation types, and maintenance practices can yield more accurate estimations of the actual contributions of green areas to ecosystem services. Also, longitudinal studies that track changes in ecosystem services provision over time can provide valuable insights into the dynamics of green areas and their resilience to environmental changes and human interventions. Long-term monitoring efforts coupled with advanced modeling techniques can offer predictive capabilities for assessing future scenarios and informing proactive conservation and management strategies. Finally, expanding the geographical scope of research beyond Brazil to include diverse regions and countries with varying ecological, cultural, and socioeconomic contexts would contribute to a more comprehensive understanding of the global significance of green areas in supporting human well-being and environmental sustainability.

5. Conclusions

Mapping ecosystem service supply and especially the quantifying information behind these maps are important contributions toward the applications of the ecosystem service approach in science as well as in practice. The mapping of this study provides a basic visualization of the supply of ES, and in this context, the location for demand from Land use/ Land cover categorizations, or within municipal districts is explicit, in this can be considered applying some approach with an ecological/ environmental direction.

Our study highlights the importance of green areas in providing a range of ecosystem services that are essential for human well-being. The results provide valuable information for policymakers and managers to design and implement effective strategies for the conservation and management of green areas in Brazil, as well as promoting the benefits of these areas for the health and well-being of the population.

CRediT authorship contribution statement

Vitória Rodrigues Ferreira Barbosa: Writing – original draft, Visualization, Formal analysis, Data curation. **Reizane Maria Damasceno:** Writing – review & editing, Software, Data curation. **Mariana Andreotti Dias:** Writing – review & editing. **Francisco Jablinski Castelhano:** Writing – review & editing, Data curation. **Henrique Llacer Roig:** Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Funding acquisition, Resources. **Weeberb J. Requia:** Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Funding acquisition, Resources.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Weeberb J Requia reports financial support was provided by National Council for Scientific and Technological Development.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.111975.

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