










Sustainable transitions in tropical reservoirs as sociotechnical systems using forest restoration for carbon footprint offsetting

Pedro G. C. Silva ^{a,*}, Marcos R. Benso ^a, Gabriela C. Gesualdo ^b, Gabriel M. Silva ^a,
Rebecca Sankarankutty^a, Danielle Bressiani ^c, Rodrigo S. Costa^d, Enio B. Pereira^d,
Josicleda D. Galvincto ^e, Adriana Cuartas ^f, Suzana M. G. L. Montenegro^g,
Denise Taffarello^{a,h}, Maarten S. Krol ⁱ and Eduardo M. Mendiondo ^{a,j}

^a Department of Hydraulic Engineering and Sanitation, São Carlos School of Engineering, University of São Paulo, São Paulo, Brazil

^b The Pennsylvania State University, State College, PA, USA

^c Water Resources Engineering, Federal University of Pelotas – UFPel, Pelotas, Brazil

^d Divisão de Impactos, Adaptação e Vulnerabilidades, INPE, São José dos Campos, Brazil

^e Centro de Filosofia e Ciências Humanas, Recife, UFPE, Brazil

^f CEMADEN, São José dos Campos, Brazil

^g Programa de Pós-Graduação em Engenharia Civil, Recife, UFPE, Brazil

^h Secretaria Municipal de Educação de São Carlos (SP), São Carlos, Brazil

ⁱ Civil Engineering and Management, University of Twente, Enschede, The Netherlands

^j Center for Water Resources & Environ. Studies CRHEA EESC USP, Itrirapina-SP, Brazil

*Corresponding author. E-mail: pedrogc.silva@usp.br

 PGCS, 0000-0003-2652-1464; MRB, 0000-0002-1237-3686; GCG, 0000-0001-6589-3397; GMS, 0000-0002-1809-0521;
DB, 0000-0002-3773-1574; JDG, 0000-0001-7367-6587; AC, 0000-0001-8993-5985; MSK, 0000-0002-6755-3692; EMM, 0000-0003-2319-2773

ABSTRACT

Tropical freshwater reservoirs are vital for water management but also contribute to greenhouse gas (GHG) emissions, making mitigation strategies crucial, especially in the Brazilian Northeast, where water scarcity and climate variability impact livelihoods and ecosystems. This semi-arid region depends on reservoirs due to irregular rainfall and high evaporation, with reforestation offering a promising means to offset emissions while supporting sustainable water management. We assessed the carbon footprint and offsetting potential of 24 small reservoirs in the region using the G-res tool under SSP2-4.5 and SSP5-8.5 climate scenarios. Results show that GHG emissions vary with water depth, climate, and land use, with smaller reservoirs often showing higher emissions. Expanding vegetation in catchments and around reservoirs can help offset emissions and enable blue-green transitions for climate change mitigation. Future reforestation efforts must increase significantly, requiring a 286% rise in forested areas compared with the reference period under the SSP5-8.5 scenario to fully offset emissions. By analyzing emissions from reservoirs and applying reforestation to reduce their carbon footprint, this study shows that (1) climate change and unsustainable transitions raise GHG emissions in tropical reservoirs, (2) reforestation can offset emissions and support sustainable management, and (3) future reforestation areas must expand under climate scenarios.

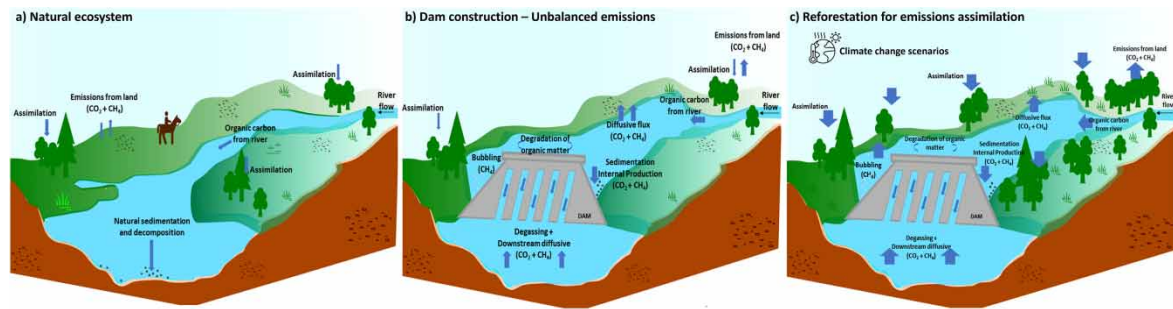
Key words: climate change adaptation, freshwater systems, GHG emissions, reforestation technique, sustainable transitions

HIGHLIGHTS

- Climate change and unsustainable transitions boost greenhouse gas (GHG) emissions in tropical reservoirs.
- Reforestation offsets reservoir GHG emissions and supports sustainable resource transitions.
- Future reforestation areas in tropical reservoirs should expand under climate scenarios.

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GRAPHICAL ABSTRACT



1. INTRODUCTION

Freshwater reservoirs are crucial for ensuring water supply stability, but can also have negative ecological impacts, such as altering catchment flows and degrading ecosystem services. They are also significant sources of greenhouse gas (GHG) emissions, influenced by factors such as biological metabolism, carbonate buffering, catchment alkalinity, thermal stratification intensity, and hydraulic retention time (Varol 2019; Hong *et al.* 2023; Leng & Koschorreck 2023). The equilibrium between GHG emissions and the carbonate buffering system is essential for determining both the overall quantity and the seasonal dynamics of methane and carbon dioxide (CH₄ and CO₂) emissions from water reservoirs (Wang *et al.* 2021). Furthermore, changes in the hydraulic retention time and the intensity of thermal stratification within reservoirs can also exert a notable impact on GHG emissions (Lu *et al.* 2020).

The concentration of GHG in surface waters is affected by input from the catchment and internal processes of the reservoir (Soued & Prairie 2021). In freshwater ecosystems, various processes play a role in the natural carbon cycle (Ion & Ene 2021). These ecosystems receive carbon from terrestrial environments via drainage, capture it through primary production, store it in sediments, release GHGs through biomass decomposition and respiration, and transport carbon downstream to seas or oceans. Polluting human activities near these ecosystems, such as untreated sewage and runoff from agriculture, can amplify the potential for GHG emissions.

While dams are often promoted as sources of clean energy, due to their ability to generate hydropower, they can also contribute to a significant increase in GHG emissions. Kumar & Sharma (2016), Deemer *et al.* (2016), and Bing (2012) have revealed significant GHG emissions stemming from reservoirs, especially in tropical regions. This phenomenon arises from the anaerobic decomposition of submerged organic matter, including vegetation and soil, primarily because dams disrupt the natural carbon cycle in freshwater ecosystems by inundating terrestrial vegetation and soil (Lu *et al.* 2020).

Thus, the decomposition of submerged organic matter in the early years following reservoir establishment leads to additional GHG emissions. Additionally, flooding can prolong the water's residence time in the reservoir, leading to increased sedimentation and decomposition, which can subsequently result in higher GHG emissions. These processes are linked to the hydromorphometric characteristics of the reservoirs (storage capacity, depth, flooded and lake area, drainage area, meteorological conditions, and land use and land cover (LULC)).

The First Brazilian Inventory of Anthropogenic Greenhouse Gas Emissions notably included reports on CO₂ and methane emissions from Brazilian hydroelectric reservoirs (MCT 2006), as did the Balcar Project (MME 2014). These reports present values of net emissions measured in field experiments and assessments based on modeling, in various scenarios.

An important finding from MCT (2006) was the weak correlation between emissions and the age of the reservoirs. This indicates that emissions are not only linked to the breakdown of existing terrestrial biomass, but also from the organic matter from upstream drainage areas, including biomass, soil carbon, sewage, and wastewater. Additionally, internal organic matter production also contributes to emissions. According to MME (2014), the calculated net GHG intensities and post-filling GHG intensities were significantly lower than emissions from thermoelectric plants, except for the Balbina reservoir (Amazon). Balbina's extensive flooded area and low generation capacity led to high GHG intensity values.

Recent studies emphasize the importance of the measurement of GHG emissions from water reservoirs (Harrison *et al.* 2021; Hansen *et al.* 2022; Soued *et al.* 2022). Hansen *et al.* (2022) found that CO₂ diffusive

fluxes were the dominant pathway for GHG emissions in many hydropower reservoirs studied. Soued *et al.* (2022) presented the dynamics of GHG emissions fluxes on reservoirs. Additionally, Harrison *et al.* (2021) emphasized the importance of reservoirs as hotspots for carbon processing and carbon-based GHG emissions, highlighting the need to study and mitigate these emissions.

Climate change can significantly impact reservoirs' GHG emissions, water quality, evaporation rates, ecological balances, and overall ecosystem health within the reservoir (Hoffner 2008; Harrison *et al.* 2021; Hansen *et al.* 2022; Soued *et al.* 2022; Acosta *et al.* 2023). To minimize the problem, reforestation can be implemented as a strategy to restore vegetation and increase GHG assimilation. The mechanism underlying this process involves photosynthesis carried out by vegetative cultures and the associated water cycle. Photosynthesis is the process by which light energy is used to synthesize glucose or sugar from CO₂ and water in the presence of chlorophyll (Urry *et al.* 2017). By the biological process of synthesizing the nutrients needed for its growth, the plant can assimilate carbon from the atmosphere in a process denoted carbon sequestration. This process can be gauged by the plant's transpiration, allowing the needed vegetation area to offset the GHG emissions of the reservoirs (Taffarello *et al.* 2019; Silva *et al.* 2021).

Reservoir GHG compensation analysis is a complex and challenging field, including the need for standardized measurement protocols, accounting for seasonal and regional variations (Goldenfum 2011; Ion & Ene 2021; Prairie *et al.* 2021; Jager *et al.* 2022). Reservoirs can act as both sources and sinks of GHG, with seasonal variations observed. Furthermore, it is essential to consider the long-term impact of GHG emissions by reservoirs, especially regarding climate change, which can exacerbate the GHG dynamic, increasing the emissions in catchments (Covey *et al.* 2021; Soued *et al.* 2022; Ballarin *et al.* 2023). Therefore, estimating the GHG impact from reservoirs is essential for implementing effective measures to minimize and mitigate their carbon footprint, and for optimizing reservoir planning and characteristics (Prairie *et al.* 2017a, b).

One of the main challenges in studying GHGs in reservoirs is understanding the complex interactions driving their emissions and identifying effective mitigation strategies. Reservoirs have unique biological, chemical, and physical processes that make emissions hard to predict and manage. Therefore, this study aims to estimate GHG emissions from 24 small reservoirs in a semi-arid region in the Brazilian Northeast under climate change scenarios and calculate the reforestation areas needed to offset these emissions. By integrating emissions estimates with reforestation strategies, this approach promotes energy efficiency, carbon sequestration initiatives,

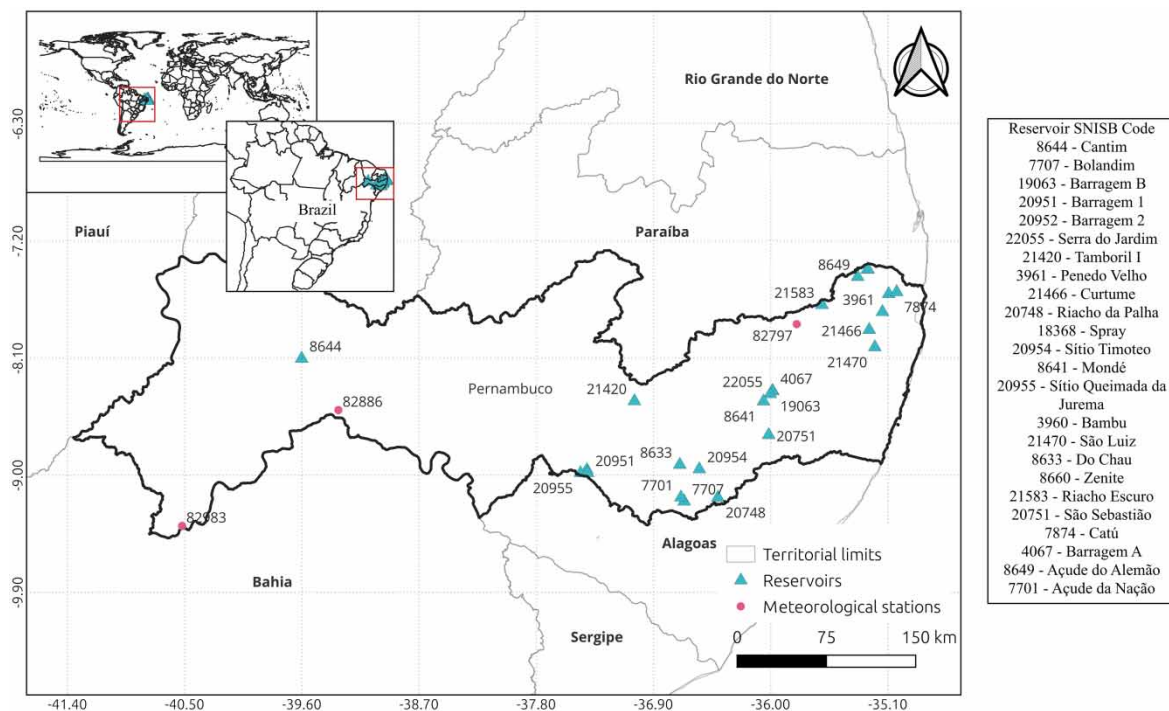


Figure 1 | Location and respective National Dam Safety Information System (SNISB) code for the 24 reservoirs in Pernambuco state, Brazil.

and informed land use and conservation policies. The goal is to identify, manage, and reduce GHG emissions to minimize the environmental impacts of reservoirs, while supporting sustainable mitigation practices. Incorporating sustainable practices and strategies for emission reduction is vital within the context of a commitment to environmental protection, and it aligns with the broader Sustainable Development Goals (SDGs) (UN 2015), including SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land).

2. METHODOLOGY

2.1. Study site

This study focuses on estimating the GHG emissions of 24 small reservoirs in the Brazilian Northeast (Figure 1), considering climate change scenarios. These reservoirs were chosen due to their distinct characteristics and regional importance, offering valuable insights into how climate dynamics affect emission patterns. The Brazilian Northeast, characterized by its semi-arid climate and recurrent droughts, poses unique challenges and opportunities for water resources management. The state of Pernambuco, where these reservoirs are located, is emblematic of this region with its irregular rainfall distribution, high evaporation rates, and reliance on reservoirs for multiple uses, such as irrigation, human supply, and industrial purposes. Understanding the dynamics of these

Table 1 | Description of hydraulic characteristics and physical parameters of the reservoirs

SNISB code	Reservoir name	Drainage catchment area (km ²)	Lake area (km ²)	Storage capacity (km ³)	Maximum depth (m)	Main stakeholder demand	Population supplied
3960	Bambu	0.02	0.003	0.020	8.0	Industrial	34,935
3961	Penedo Velho	0.60	0.089	0.234	6.5	Irrigation	13,867
4067	Barragem A	1.17	0.216	0.013	6.0	Irrigation	378,052
7701	Açude da Nação	0.80	0.110	0.263	12.0	Human supply	44,260
7707	Bolandim	6.10	0.980	0.120	18.0	Human supply	44,260
7874	Catú	12.86	0.004	0.018	5.0	Irrigation	81,042
8633	Do Chau	12.76	0.010	0.110	9.0	Flow regularization	12,199
8641	Mondé	0.16	0.040	0.110	8.0	Human supply	20,674
8644	Cantim	0.80	0.230	0.088	5.0	Flow regularization	18,612
8649	Açude do Alemão	0.90	0.070	0.013	4.0	Flow regularization	46,147
8660	Zenite	69.40	0.002	0.003	7.0	Human supply	24,587
18368	Spray	12.78	0.003	0.020	5.0	Flow regularization	7,750
19063	Barragem B	1.17	0.450	0.049	6.0	Recreation	378,052
20748	Riacho da Palha	20.00	0.001	0.020	15.0	Human supply	17,131
20751	São Sebastião	18.53	0.013	0.250	20.0	Human supply	22,991
20951	Barragem 1	1.17	0.043	0.051	7.0	Irrigation	32,650
20952	Barragem 2	1.17	0.043	0.051	7.0	Irrigation	32,650
20954	Sítio Timoteo	69.40	0.002	0.050	5.0	Irrigation	9,079
20955	Sítio Queimada da Jurema	0.01	0.030	0.020	3.0	Irrigation	32,650
21420	Tamboril I	0.72	0.028	0.114	8.0	Human supply	74,822
21466	Curtume	1.10	0.150	0.002	17.0	Industrial	79,293
21470	São Luiz	10.59	0.020	0.110	5.0	Industrial	111,243
21583	Riacho Escuro	12.86	0.010	0.037	3.7	Flow regularization	21,808
22055	Serra do Jardim	0.34	0.004	0.200	10.0	Human supply	23,779

Source: SNISB/ANA (2023).

reservoirs is critical in a region where water scarcity and climate variability significantly impact livelihoods and ecosystems.

2.2. Data acquisition

Reservoir data, including hydrological and physical parameters, were obtained through the National Dam Safety Information System platform, provided by the Brazilian National Water and Sanitation Agency (SNISB/ANA 2023). Table 1 shows the selected reservoirs and their main characteristics.

The Brazilian National Water and Sanitation Agency (ANA) plays a pivotal role in managing and regulating the country's water resources. ANA provides valuable information about reservoir levels, water quantity, and quality, which are crucial for water resource management, hydropower generation, and drought mitigation. Access to ANA's reservoir data (ANA 2019) enables authorities to make informed decisions regarding water allocation and conservation, especially in a large country like Brazil, where water resources are distributed unevenly, with some regions living in abundance and others experiencing water scarcity (Bressiani *et al.* 2015). Land use and land cover in the area of the reservoirs was acquired from MapBiomas Project (2023).

Meteorological data were obtained from the Brazilian National Institute of Meteorology (INMET 2022). The data required for this study (monthly temperature and wind speed) were collected for 30 years (1991–2020), from three stations: 82886 – Cabrobo; 82983 – Petrolina; and 82797 – Surubim (Figure 2).

2.3. G-res tool

We applied the G-res tool to estimate and report net GHG emissions from reservoirs. G-res is a web-based tool for hydropower companies and researchers to estimate and report net GHG emissions from a reservoir (Prairie 2017b). The essence of the G-res tool is rooted in a collection of empirical models crafted through a synthesis of published literature regarding reservoir emissions (Prairie *et al.* 2021). These models are based on the influence of local to regional environmental controls on GHG emission and on the characteristics of the individual reservoirs and their catchments (Prairie *et al.* 2021). They also consider the unique attributes of individual reservoirs and their respective catchment areas.

The G-res tool employs a biogeochemical modeling approach to estimate the net GHG footprint of reservoirs by comparing emissions before and after impoundment over a 100-year lifetime. It calculates baseline emissions from the natural landscape before flooding and post-impoundment emissions from the reservoir, including

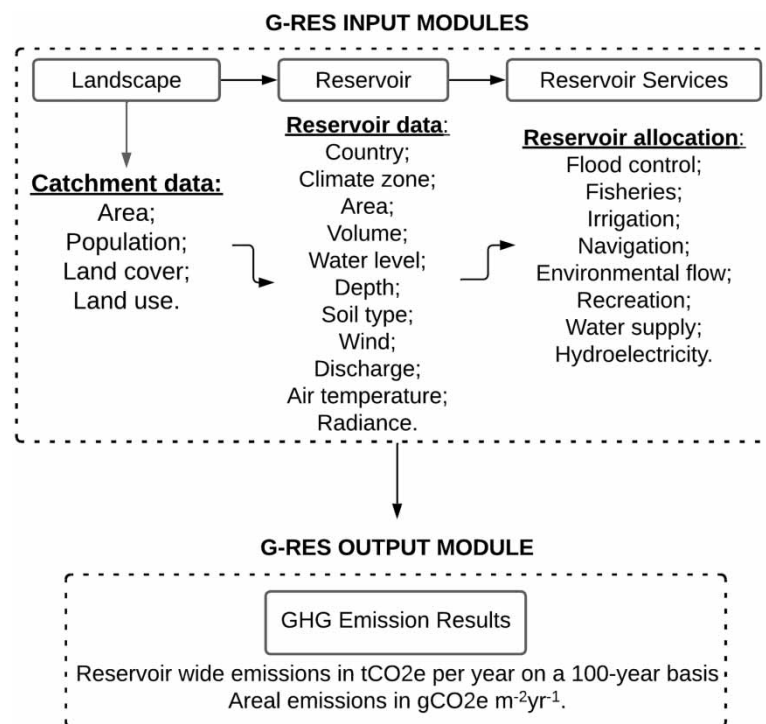


Figure 2 | G-res tool modules, input parameters, and output results.

methane (CH₄) and CO₂ releases. The tool also assesses the impact of nutrient enrichment from human-induced phosphorus inputs (Unrelated Anthropogenic Sources, UAS), though these emissions are not excluded from the total footprint. By subtracting baseline emissions from post-impoundment emissions, the tool determines the net impact of reservoir creation and helps allocate emissions to specific services or human activities. The methodology is detailed in the G-res Tool Technical Document (Prairie *et al.* 2017a, b).

The tool contains six main modules: (1) Landscape, (2) Reservoir, (3) Reservoir Services, (4) GHG emissions results, (5) Earth Engine, and (6) Complementary Modules. In this paper, we used the four initial modules (Figure 2). First, on Landscape, it is necessary to enter data for the land cover in the catchment area, catchment population, and the reservoir area; the Landscape worksheet contains the required inputs that describe the catchment within which the reservoir is located. The reservoir module has information about the key parameters of the water body and the air temperature measured for the area. Finally, the Reservoir Services module permits inserting the demand type, and reservoir water usage, e.g., hydroelectricity, flood control, irrigation, and water supply. The module GHG emissions results provide the total carbon footprint of the reservoir.

2.4. Transitions in socioeconomic patterns: pathways, and implications for the GHG emissions

We used the Shared Socioeconomic Pathways (SSPs) combined with the Representative Concentration Pathways (RCPs) as a climate change force. SSPs combined with the RCPs are scenarios developed to anticipate future global challenges. They represent distinct transitions of societal development and associated GHG emissions, providing crucial context for climate modeling and policy design, and making it possible to permit, simulate, and explore the impacts of climate change on ecosystem services. Among these, SSP2-4.5 and SSP5-8.5 are particularly noteworthy (O'Neill *et al.* 2017).

SSP2-4.5 is the 'middle of the road' scenario. It assumes a world that progresses moderately, without significant societal shifts toward sustainability or the opposite (O'Neill *et al.* 2017). This pathway anticipates modest reductions in GHG emissions, largely due to technological advancements and incremental changes in social and economic structures. For climate researchers and policymakers, SSP2-4.5 offers a trajectory serving as a balanced benchmark for potential future developments.

In contrast, SSP5-8.5 paints a picture of a world characterized by rapid economic growth and fast-paced urbanization, driven by fossil-fueled development (O'Neill *et al.* 2017). This scenario projects the highest global average temperature increases among all SSPs. It embodies a future where energy demand is met predominantly by carbon-intensive sources, leading to significant climate challenges. For those working on climate change mitigation strategies, SSP5-8.5 serves as a critical reminder of the possible repercussions of continued reliance on fossil fuels and the urgency of transitioning to sustainable energy sources.

The distinction between SSP2-4.5 and SSP5-8.5 underscores the wide-ranging potential futures our planet faces depending on human choices. These pathways not only serve as tools for climate modeling but also as crucial guides for policymakers (Riahi *et al.* 2017; Miralles-Wilhelm 2022). The differences in environmental, societal, and economic outcomes projected by these SSPs emphasize the importance of proactive, informed, and strategic decision-making today (van Vuuren *et al.* 2011). SSP2-4.5 suggests a future where adaptation and mitigation can be more manageable, while SSP5-8.5 is a stark reminder of the perils of unchecked economic ambitions without regard for environmental sustainability.

2.5. Carbon assimilation and reforestation

To calculate carbon assimilation in this study, we applied a methodology consisting of three stages: (1) water balance; (2) photosynthesis/carbon assimilation; and (3) piezometric line analysis, following the ones proposed by Silva *et al.* (2021) and Taffarello *et al.* (2019).

Firstly, the study examined the water balance (1) by accounting for water inputs from precipitation (P) and losses through evapotranspiration (ET) (P-ET). The Thornthwaite (1948) method was employed to compute potential ET. This is a temperature-based single-factor method and therefore can avoid increasing error due to other unknown meteorological variables. Secondly, we used the connection established by Silva *et al.* (2021) between plant carbon sequestration and climatic conditions (2). The net radiation, determined from the water balance analysis, was considered equated to the Photosynthetically Active Radiation (PAR), which plants use in the process of photosynthesis. The energy from this radiation was related to carbon assimilation, converting it into glucose formation using a specific equation. Thirdly, as the piezometric line analysis (3), plant transpiration was analogized to a water pump, detailing the water flow from the soil up to its ET.

Table 2 | Temperature and wind speed for Pernambuco state

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°C)												
Reference	25.30	25.16	24.70	23.62	21.99	20.81	20.29	21.89	22.80	24.22	24.63	25.13
SSP2-4.5	27.80	27.66	27.20	26.12	24.49	23.31	22.79	24.39	25.30	26.72	27.13	27.63
SSP5-8.5	29.80	29.66	29.20	28.12	26.49	25.31	24.79	26.39	27.30	28.72	29.13	29.63
Wind speed (m/s)												
	1.74	1.81	1.72	1.66	1.69	1.81	1.96	2.15	2.29	2.22	2.12	1.90

Additionally, potential energy differences across various plant parts, like the roots and leaves, were calculated. Comparisons were also drawn between different plant types to understand their efficiency in water use, carbon assimilation, and responses under the climate scenarios. A mathematical description of the equations used is available in Supplementary Appendix A.

2.5.1. Climate variables

In examining climatological aspects, we focused on two key variables, monthly temperature and wind speed, with the G-res Tool. Our study accounted for temperature increases of approximately 2.5 and 4.5 °C, from 2020 to 2100, for SSP2-4.5 and SSP5-8.5, respectively, based on [IPCC Projections \(2022\)](#). This allowed simulating extreme perspectives for each reservoir and comparing the simulations with the reference ([Table 2](#)).

3. RESULTS AND DISCUSSION

3.1. Current carbon emissions from reservoirs

The emissions of GHGs (in CO₂ equivalent: CO₂e) across the group of reservoirs exhibited notable variability, ranging from 55 to 22,538 gCO₂e m⁻² year⁻¹. This observed diversity underscores the distinct behavior of

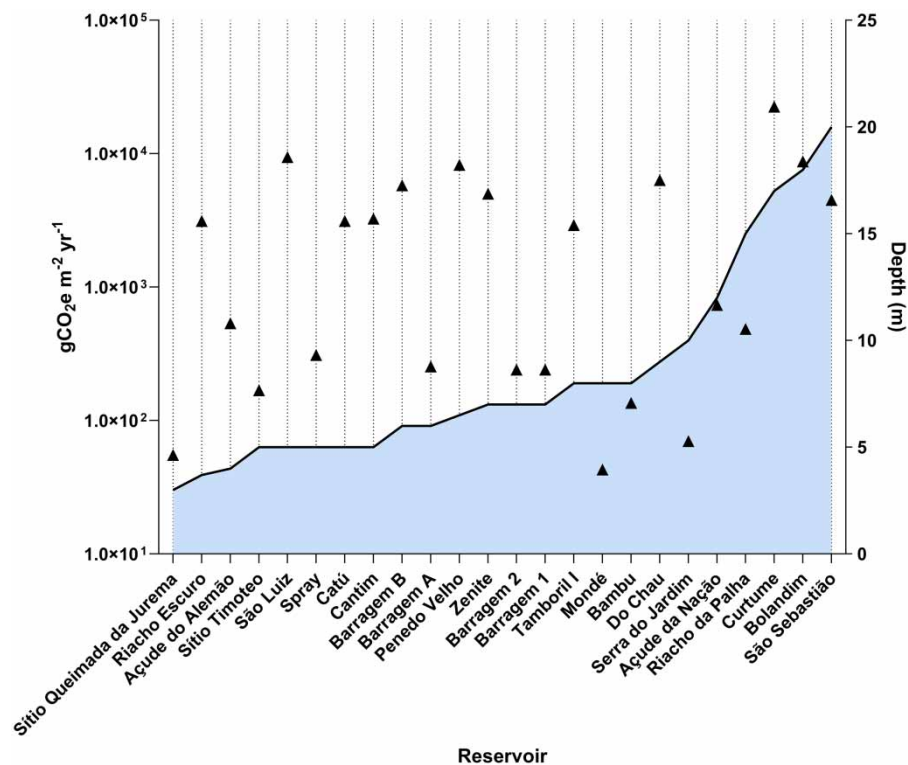


Figure 3 | GHG emissions for each reservoir in gCO₂e, regarding depth. The bold line represents the depth, and the triangle points to the gCO₂e emissions on a logarithmic scale.

reservoirs within the same regional context regarding the dynamic interplay between the water column and the atmosphere. In a general sense, reservoirs characterized by larger lake areas tended to display elevated emissions, emphasizing the significance of this parameter in assessing the ecological impacts within their respective ecosystems. When we analyze the depth of reservoirs, in general, the deeper the reservoir, the higher the GHG emissions (Figure 3).

As depicted in Figure 5, the Curtume reservoir, encompassing a lake area of 0.15 km², registered the highest emissions at approximately 22,538 gCO₂e m⁻² year⁻¹. Nevertheless, reservoirs featuring smaller lake areas, such as Do Chau (lake area: 0.01 km²), Riacho Escuro (lake area: 0.01 km²), São Sebastião (lake area: 0.013 km²), and São Luiz (lake area: 0.02 km²), exhibited noteworthy emissions, which varied from 3,126 to 9,440 gCO₂e m⁻² year⁻¹.

This observed variability can be attributed, in part, to the enhanced storage capacity of these reservoirs, collectively representing around 26% of the combined capacity of the 24 reservoirs in the present study. Nonetheless, other parameters could be involved in those results, including the trophic state of the reservoir and the sediments in the water column. Furthermore, the water residence time emerges as another important factor, as it influences the decomposition of organic materials within the aquatic dynamic, which is also linked to the depth of the reservoir.

When observing the demands associated with the reservoirs, the emission levels follow the classification, from major to minor: (1) Industrial; (2) Human supply; (3) Flow regularization; (4) Irrigation; and (5) Recreation (Figure 4).

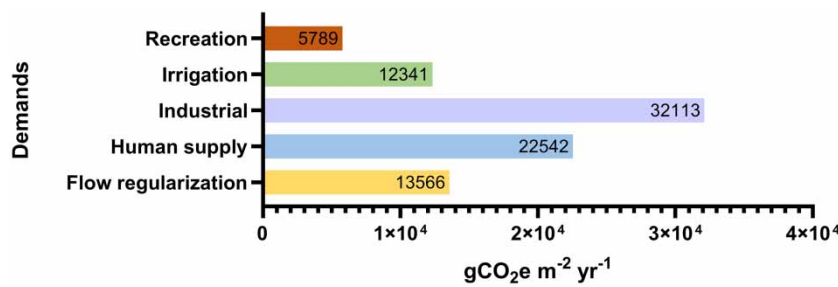


Figure 4 | GHG emissions by demand for all reservoirs in gCO₂e m⁻² year⁻¹.

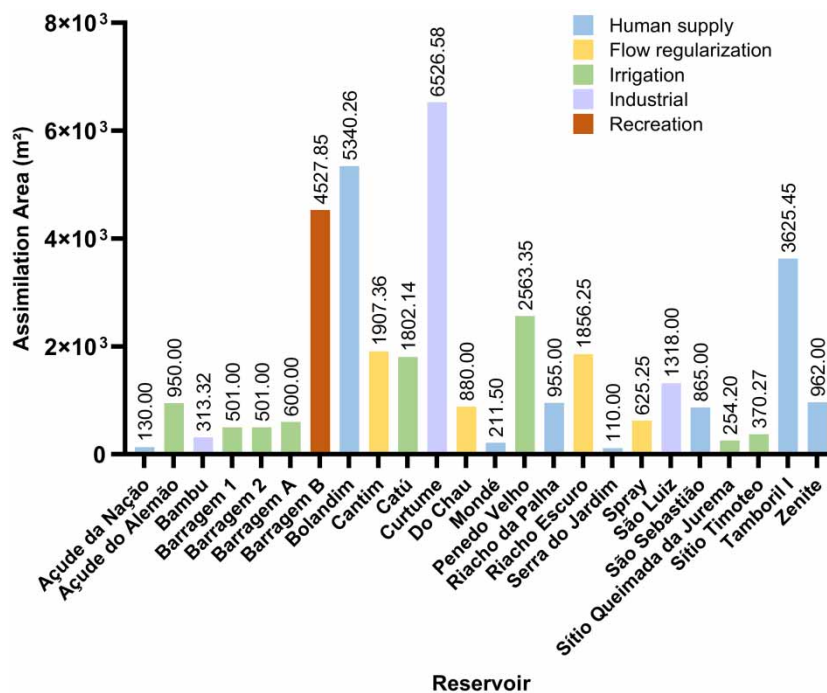


Figure 5 | Assimilation areas are needed to compensate for the GHG emissions of each reservoir.

3.1.1. GHG compensation analysis

GHG compensation analysis in reservoirs examines emissions and carbon sequestration processes associated with artificial water reservoirs, such as dams and impoundments. Reservoirs can have complex and variable effects on the carbon and GHG balance in the environment due to their construction and management.

Following the results presented in the previous section, the necessary reforestation areas are proportional to the GHG emissions (Figure 5). The Curtume reservoir has the highest reforestation area required, around 6,600 m², and the minimum area required was 110 m² for the Serra do Jardim reservoir. The mechanisms associated with these processes include the decomposition of submerged organic matter, methane production in anoxic sediments, and the diffusion of GHGs from the water surface into the atmosphere. Depending on the aquatic dynamics associated with it, the required area can be affected by these parameters.

Although the Industrial Service sector exhibits the highest GHG emission rates, an intriguing pattern emerges when considering the cumulative reforestation areas required: the Human Supply sector shows the largest values. This phenomenon can be attributed to the type of vegetation used for offsetting emissions, which significantly influences the outcomes due to its capacity to efficiently assimilate carbon through photosynthesis. Furthermore, this impact on results is mirrored in the Flow Regularization and Recreation sectors, which exhibit contrasting patterns compared with GHG emissions, as illustrated in Figure 5.

3.2. Future climate projections: GHG emissions by reservoirs

The investigation of GHG emissions from reservoirs considering future scenarios holds the potential to elucidate the dynamics of long-term emissions. Such insights bear significant implications across various sectors, encompassing economic, health, biodiversity, social, and cultural perspectives. If society persists with unsustainable practices without embracing a green transition, it risks amplifying the adverse impacts of global warming.

3.2.1. GHG emissions and reforestation fraction – reference

To facilitate a comprehensive comparative analysis of the results, the investigation centered on the proportion of reforestation areas concerning the reservoir's lake area. As illustrated in Figure 6(a), a clear inverse relationship is observed between the extent of the reservoir's lake area and the corresponding reforestation fraction (dimensionless) required to mitigate GHG emissions. This correlation stems from the inherent proportionality between these two parameters. Hence, it becomes evident that reservoirs featuring larger lake areas are likely to require a smaller reforestation fraction for effective GHG emission offset.

Upon conducting a more comprehensive examination of the relationship between GHG emissions and the reforestation fraction, an intricate pattern emerges. It becomes evident that reservoirs' behavior in this context is characterized by a notable and diverse range of responses. This heterogeneity underscores the multifaceted interplay between GHG emissions and the reforestation fraction within different reservoirs (Figure 6(b)), suggesting that one single approach may not be suitable to address the complex dynamics at play.

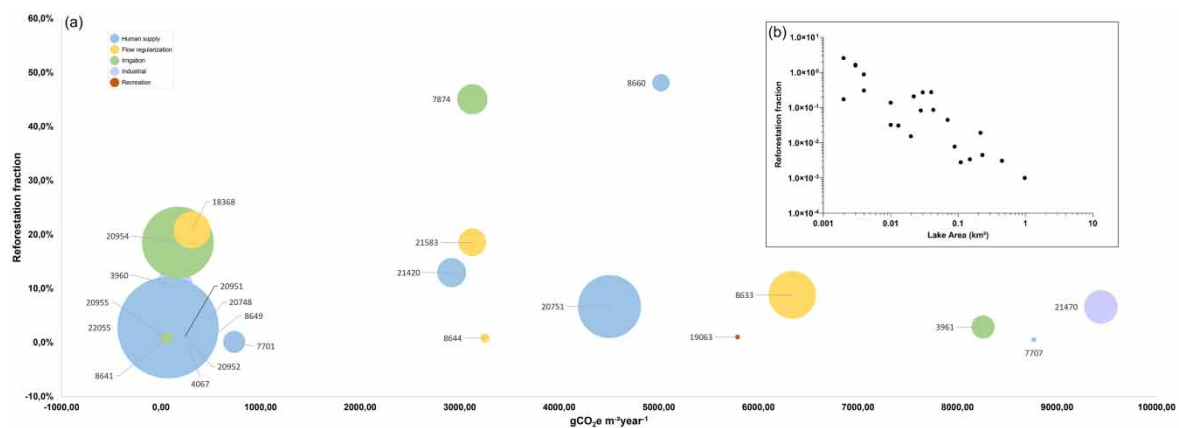


Figure 6 | (a) Relationship between reforestation fraction and lake area of each reservoir for the reference. The size of the circles corresponds to the equivalent depth storage, which represents a relation between the storage capacity and the lake area of the reservoir. The numbers near the circles are the SNISB code of the respective reservoir. Negative values are adjustments of the axes. (b) Correspondence of GHG emissions and reforestation fraction. Axes are represented on a logarithmic scale with base 10.

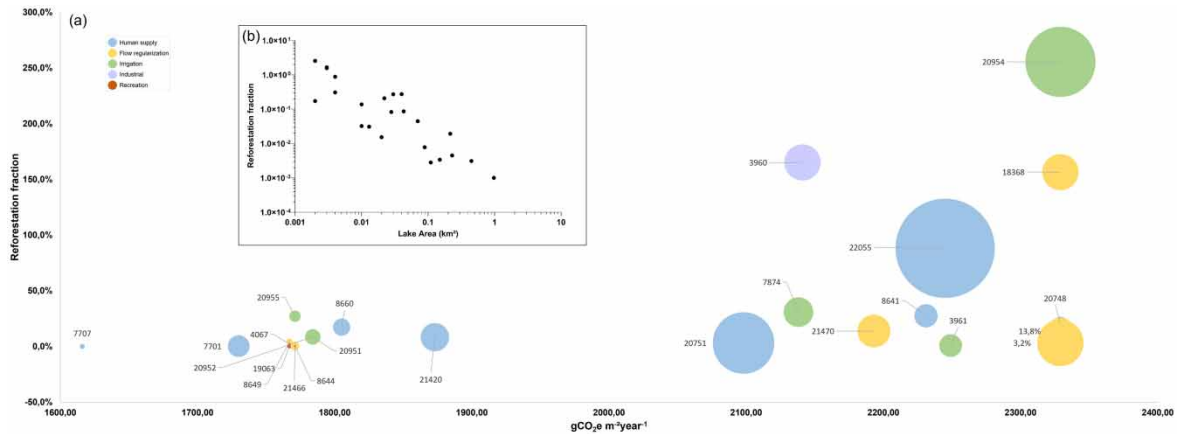


Figure 7 | (a) Correspondence of GHG emissions and reforestation fraction for the SSP2-4.5 scenario. The size of the circles corresponds to the equivalent depth storage, which represents a relationship between the capacity and lake area of the reservoir. The numbers near the circles are the SNISB codes of the reservoirs. Negative values are adjustments of the axes. (b) Relation of reforestation fraction and lake area of each reservoir for the SSP2-4.5 scenario. Axes are represented on a logarithmic scale.

3.2.2. GHG emissions and reforestation fraction – SSP2-4.5 scenario

Figure 7(a) reveals notable changes in the positions of certain reservoirs compared with the reference, indicating a significant trend. These shifts can be related to the impact of rising temperatures and the associated increase in radiation levels under the current scenario, which can alter the aquatic dynamics of the reservoir, leading to an increase in CO₂e emissions.

As temperatures increase, the radiation conditions of these reservoirs are altered, impacting their ecological and environmental dynamics. The interaction between temperature and radiation in these aquatic systems can potentially trigger a cascade effect, influencing not only the reservoirs themselves but also the surrounding ecosystems. This highlights the complex interconnections of environmental changes in response to global warming, underlining the importance of ongoing research and management strategies to address these evolving challenges.

The results for the SSP2-4.5 scenario align with the reference trend (Figure 7(b)). However, a significant increase in the reforestation fraction can be observed. Across all reservoirs, the reforestation area needed grows substantially by 286% (from approximately 2.19 to 8.45). This increase highlights the impact of climate change on the dynamics of GHG emissions in these reservoirs.

3.2.3. GHG emissions and reforestation fraction – SSP5-8.5 scenario

The effect attributed to the temperature changes proved insufficient to promote such different results in both scenarios of GHG emissions (SSP2-4.5 and SSP5-8.5) and, consequently, larger reforestation areas. In Figure 8(a), the variations attributed to the heightened temperatures within the current scenario do not appear markedly dissimilar to those observed in the previous scenario (SSP2-4.5). The trends of the necessary reforestation fraction have almost the same values compared with the previous scenario (Figure 8(b)). The increase in the reforestation fraction, compared with the reference, could reach the amount of 5.99, approximately. This value is slightly inferior to the SSP2-4.5 scenario, but it is expressive and represents an increase of 276% in relation to the reference scenario. Some reservoirs showed a different pattern, which was expected due to the changes in the climatological variables.

It has been observed that LULC play a crucial role in this pattern. This means that the use and coverage of land in the areas surrounding a reservoir have a significant impact on the associated GHG emissions. The close relationship between LULC and GHG emissions underscores the critical importance of effective land management and usage in the areas adjoining the catchments that contribute to the reservoirs.

Furthermore, the interactions between the catchment (the drainage area contributing to the reservoir's water supply) and the reservoir itself are critical when it comes to GHG emissions. The way water flows, the surrounding vegetation, seasonal changes, and human activities in the catchment can significantly influence the GHG emissions from the reservoir. Therefore, understanding and effectively managing these interactions are essential

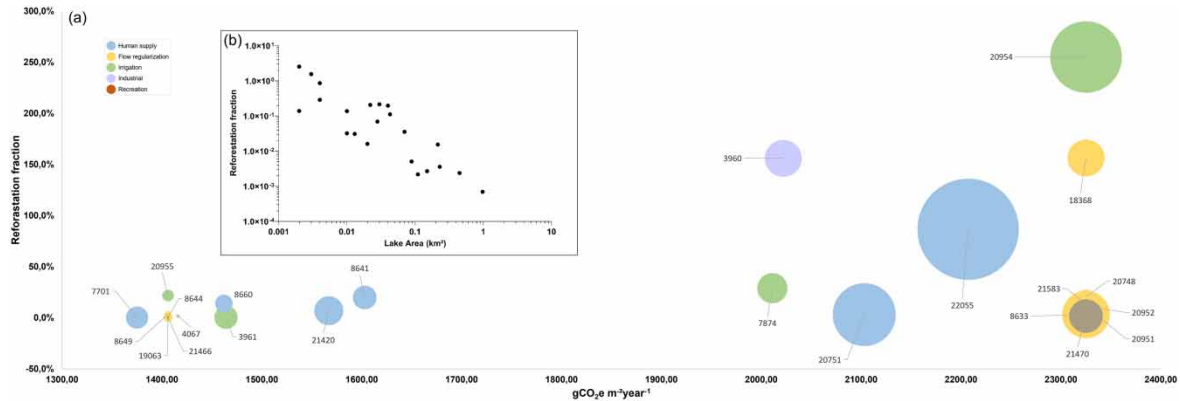


Figure 8 | (a) Correspondence of GHG emissions and reforestation fraction for the SSP5-8.5 scenario. The size of the circles corresponds to the equivalent depth storage, which represents a relationship between the capacity and lake area of the reservoir. The numbers near the circles are the SNISB codes of the reservoirs. Negative values are adjustments of the axes. (b) Relation of reforestation fraction and lake area of each reservoir for the SSP5-8.5 scenario. Axes are represented on a logarithmic scale.

for reducing GHG emissions associated with reservoirs. The results for Lobo Reservoir as a case study for hydro-power reservoir emissions are provided in Supplementary Appendix B.

4. CONCLUSIONS AND REMARKS

As the world grapples with the immediate and long-term challenges of climate change, the insights provided by SSP-RCP scenarios are invaluable. They reaffirm the interconnectedness of global systems – how societal choices, economic trajectories, and environmental outcomes are intrinsically linked. In this present paper, we analyzed the GHG emissions of 24 reservoirs in the semi-arid region in the Brazilian Northeast, observing a striking range from 55 to $22,538 \text{ gCO}_2\text{e m}^{-2} \text{ year}^{-1}$. Additionally, we determined that future reforestation efforts would need to increase by up to 286% to fully offset these emissions under the SSP5-8.5 scenario. The reservoirs present heterogeneous responses to the carbon footprint, requiring interventions to offset emissions, with reforestation emerging as a promising approach under climate change scenarios.

The variability in GHG emissions can be primarily attributed to three major variables: reservoir water depth, climate and temperature conditions, and LULC. Larger reservoirs tend to have a greater water storage capacity and may therefore have a larger influence on GHG emissions, but their emission intensity per m^2 is generally lower, related to reservoirs with larger water depths. Nonetheless, the impact of smaller reservoirs depends on factors such as the age of the reservoir and specific characteristics, including the microbial decomposition of organic matter in submerged soils and sediments, as well as the inundation of terrestrial vegetation.

It is imperative to acknowledge that these emissions can have substantial environmental and climatic impacts, underscoring the need to consider them in research and management efforts, especially for smaller and more shallow water bodies with high emission intensities. The local climate and seasonal temperature fluctuations in the reservoir's region play a crucial role in elucidating the behavior of these reservoirs, both in reference and under climate change scenarios. Further research should also explore the changes in LULC. Managing these aspects can greatly influence the dynamic of the carbon fluxes, as well as the inflow of organic material in the runoff fluxes in the catchment. Implementing tools such as the Soil and Water Assessment Tool (SWAT), widely used in assessing soil erosion prevention and control, non-point source pollution control, hydrological estimations, and regional management in catchments, as well as the under-development Brazilian Ecohydrological Simulation Tool (BEST), could support such investigations.

Despite these challenges, applying relatively straightforward actions, such as expanding vegetation areas in the catchment and around reservoirs, can yield substantial environmental benefits and contribute to the promotion of more sustainable practices. This approach offers the prospect of significantly mitigating the effects of climate change and fostering improvements in ecosystem services for a more sustainable future.

Moreover, the findings of this study underscore the necessity of integrating emission reduction efforts into broader water resource and landscape management policies. Such policies should not only focus on mitigating

GHG emissions but also promote biodiversity conservation, water quality improvements, and the resilience of aquatic ecosystems. Multidisciplinary and cross-sectoral collaborations will be essential to achieving these goals, ensuring that mitigation efforts align with social and economic priorities and that they are tailored to regional and local contexts.

Finally, by quantifying the reforestation areas needed to offset emissions and by identifying the main drivers of GHG emissions in small reservoirs, this study contributes to the growing body of knowledge that supports evidence-based decision-making. It emphasizes the need for robust monitoring frameworks and adaptive management approaches that can respond to new insights and changing environmental conditions. Moving forward, integrating these scientific findings into practice will be vital to curbing the carbon footprint of water reservoirs and fostering more sustainable development pathways in semi-arid regions and beyond.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: <https://doi.org/10.5281/zenodo.17624178>.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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