

# Assessing forest cover and CO<sub>2</sub> emissions in portuguese-speaking countries and China: a comparative remote sensing approach

*Isaú Alfredo B. Quissindo*

José Eduardo dos Santos University, Angola  
University of Trier, Germany

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## Abstract

This study provides an integrated comparative assessment of forest cover dynamics and CO<sub>2</sub> emissions across Portuguese-speaking countries and China from 2001 to 2024, using satellite-based datasets derived from Hansen's Global Forest Change and Global Forest Watch. The analysis combines Landsat-derived forest metrics with CO<sub>2</sub> emission estimates to characterise temporal trends and spatial heterogeneity in forest change processes. Results show pronounced geographical contrasts: Brazil and China together account for nearly 99% of the total aboveground carbon stocks and more than 80% of CO<sub>2</sub> emissions linked to forest cover loss. Brazil's emissions stem mainly from continued deforestation and degradation in tropical biomes, while China's extensive reforestation and afforestation efforts have partially offset earlier losses. In sub-Saharan Africa, Angola and Mozambique exhibit moderate but persistent forest decline, driven by agricultural expansion, charcoal production, and recurrent fire disturbance. Conversely, smaller island nations such as São Tomé and Príncipe, Cape Verde, and Timor-Leste display negligible forest loss, reflecting stable land-use patterns but limited forest area. Portugal represents an intermediate case, where wildfire-driven losses dominate. Overall, these patterns demonstrate that large tropical and subtropical countries play a disproportionate role in regional and global forest-carbon balances. Strengthening land-use governance, promoting sustainable forest management, and expanding reforestation programmes are critical to maintaining carbon sequestration capacity and mitigating climate-related risks across Lusophone and Asian contexts. The findings underscore the importance of harmonised monitoring systems and policy coordination to achieve long-term forest sustainability and emission reduction goals.

**Keywords:** Forest Dynamics, Time Series, Carbon Sequestration, Lusophony, Landsat collection.

## Resumo

Este estudo apresenta uma avaliação comparativa e integrada da dinâmica da cobertura florestal e das emissões de CO<sub>2</sub> nos países de expressão portuguesa e na China, no período de 2001 a 2024, utilizando dados de satélite provenientes dos conjuntos Global Forest Change de Hansen e Global Forest Watch. A análise combina métricas florestais derivadas de imagens Landsat com estimativas de emissões de CO<sub>2</sub>, de modo a caracterizar as tendências temporais e a heterogeneidade espacial dos processos de alteração florestal. Os resultados revelam contrastes geográficos marcantes: o Brasil e a China concentram juntos cerca de 99% do total de carbono acima do solo e mais de 80% das emissões de CO<sub>2</sub> associadas à perda de cobertura florestal. As emissões do Brasil resultam principalmente da continuidade da desflorestação e degradação nos biomas tropicais, enquanto os programas de reflorestamento e florestação da China têm compensado parcialmente as perdas anteriores. Na África Subariana, Angola e Moçambique apresentam um declínio florestal moderado, mas per-

sistente, impulsionado pela expansão agrícola, produção de carvão vegetal e ocorrência frequente de incêndios. Por outro lado, pequenos Estados insulares como São Tomé e Príncipe, Cabo Verde e Timor-Leste registam perdas florestais praticamente insignificantes, refletindo padrões de uso da terra estáveis, embora com áreas florestais limitadas. Portugal situa-se num nível intermédio, onde as perdas são maioritariamente provocadas por incêndios florestais. De forma geral, estes padrões demonstram que os grandes países tropicais e subtropicais desempenham um papel desproporcional no equilíbrio florestal e de carbono, tanto a nível regional como global. O reforço da governação do uso da terra, a promoção da gestão florestal sustentável e a expansão dos programas de reflorestamento são fundamentais para manter a capacidade de sequestro de carbono e mitigar os riscos associados às mudanças climáticas nos contextos lusófono e asiático. Os resultados reforçam a importância de sistemas de monitorização harmonizados e de uma coordenação política eficaz para alcançar a sustentabilidade florestal e a redução de emissões a longo prazo.

**Palavras-chave:** Dinâmica Florestal, Séries Temporais, Sequestro de Carbono, Lusofonia, Coleção Landsat.

## 1. Introduction

Forests are a critical component of the global carbon cycle, serving as essential sinks that absorb and store atmospheric carbon dioxide (CO<sub>2</sub>) in biomass and soil, mitigating approximately 25 % of anthropogenic carbon emissions (Mo et al., 2023). However, pressures such as deforestation, forest degradation, and climate-induced extreme events can turn forests from carbon sinks into net CO<sub>2</sub> sources. Beyond carbon storage, forests also sustain biodiversity and ecosystem functioning: changes in forest cover affect habitat connectivity, ecological resilience, and species diversity, linking carbon dynamics closely with biodiversity outcomes (Basso et al., 2023; Ahmad et al., 2022; Baccini et al., 2012). Integrated assessments of forest change are therefore essential to address the combined climate and ecological challenges facing forested regions worldwide.

Robust and continuous monitoring of forest cover and its temporal dynamics has become a scientific and policy imperative, particularly for supporting the formulation, verification, and implementation of climate policies and mitigation targets, such as those set by the Paris (Calders et al., 2020). Remote Sensing (RS) has emerged as an indispensable tool in this regard: data from optical satellites, radar systems, and LiDAR have revolutionised our ability to map and analyse forest carbon across local to global scales (Liang et al., 2025).

Applying these methods to specific geographic contexts (such as China and Portuguese-speaking countries) offers a unique opportunity to explore contrasting land-use trajectories, conservation strategies, and institutional frameworks. In this study, Lusophony is not treated merely as a linguistic grouping, but as a set of countries linked by shared historical legacies, governance traditions, and cooperation frameworks, including environmental and climate-related initiatives within the Community of Portuguese Language Countries (CPLP). These shared institutional and policy contexts coexist with marked ecological, socioeconomic,

and developmental heterogeneity. China, for example, has implemented large-scale reforestation programmes, contributing to an estimated annual net carbon sink of approximately 0.22 Pg C/yr, equivalent to 11.5–14.9 % of its fossil fuel and industrial emissions (Cai et al., 2025). Conversely, Portuguese-speaking countries exhibit rich ecosystem diversity (from the Amazon and African tropical forests to European temperate woodlands) alongside varying socioeconomic conditions and forest management practices. This combination of common historical-political ties and diverse ecological realities provides a valuable basis for comparative analysis of forest dynamics and associated carbon emissions.

Furthermore, the global scientific community is developing new space-based platforms, such as the ESA's Biomass mission equipped with P-band synthetic aperture radar to produce detailed three-dimensional maps of forest biomass in remote tropical regions, enabling more reliable estimates of stored carbon and its temporal fluxes (Liang et al., 2025; Mo et al., 2023; Calders et al., 2020).

The integration of multi-source geospatial data and open-access analytical tools ensures methodological transparency, scalability, and reproducibility in this study. By leveraging harmonised datasets such as Hansen Global Forest Change (GFC) v1.12 dataset and Global Forest Watch (GFW)'s CO<sub>2</sub> emissions models, combined with the cloud-based computational capacity of Google Earth Engine (GEE) and Python-based analytics in Google Colab (GC) pro, this approach enables the generation of consistent, high-resolution insights across contrasting geographical contexts. Such integration not only enhances the precision of forest change detection and emission estimation but also facilitates the exploration of spatial heterogeneity and temporal dynamics within and between regions. Ultimately, this data-driven and reproducible framework provides a scientifically rigorous foundation for cross-national comparison, supporting the development of targeted strategies for sustainable forest management and climate change mitigation in Portuguese-speaking countries and China.

The convergence of these technological advances with statistical and process-based models (integrating field data, forest inventories, and remote observations) constitutes the most promising path towards quantifying, comparing, and understanding forest carbon dynamics across diverse regional realities. This study therefore aims to investigate and contrast the trajectories of forest cover and CO<sub>2</sub> emissions in China and Portuguese-speaking countries, providing robust insights for mitigation and conservation policies tailored to regional specificities.

This study aims to provide an integrated comparative assessment of forest cover dynamics and CO<sub>2</sub> emissions in Portuguese-speaking countries and China, using remote-sensing-derived metrics, with a view to informing climate policies and mitigation strategies adapted to regional specificities.

The specific objectives are: (i) To evaluate the spatial and temporal variation of forest cover in Portuguese-speaking countries and China from 2001 to 2024 using Landsat-derived Global Forest Change data (Hansen et al., 2013); (ii) To quantify CO<sub>2</sub> emissions associated with changes in forest cover, identifying association between deforestation, forest degradation, and land-use dynamics; (iii) To compare patterns and trends of forest change and CO<sub>2</sub> emissions between Portuguese-speaking countries and China, highlighting similarities, differences, and potential socio-economic and environmental explanatory factors.

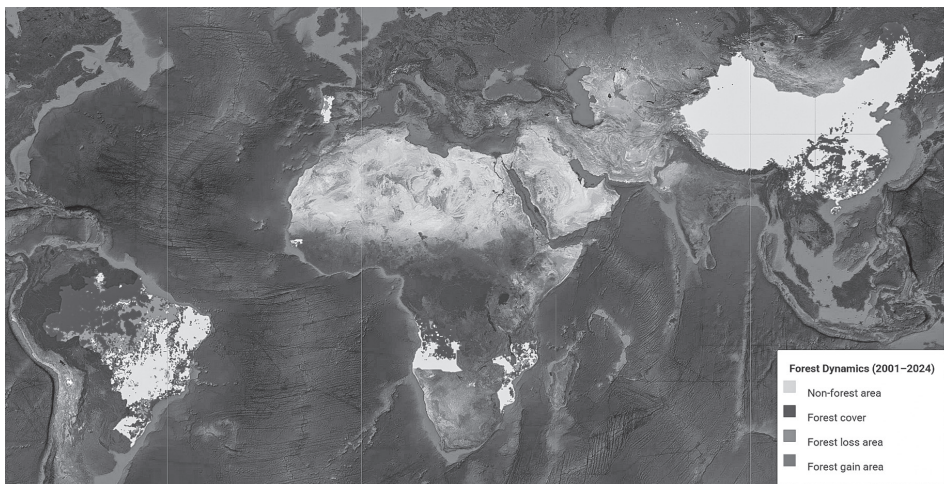
## 2. Materials and Methods

### 2.1. Study area

The study area encompasses all countries where Portuguese is the official language, collectively known as the Lusophone world, which extends across four continents: Africa, South America, Europe, and Asia (Figure 1). Each of these nations presents unique ecological characteristics, particularly in terms of forest types, which are deeply shaped by their climatic conditions, biogeographical settings, and anthropogenic influences.

In this session, Figure 1 illustrates only the geographic context; the interpretation of forest dynamics is presented in the Results section.

**Figure 1.** Forest dynamics from 2001 to 2024 in the study area.



In Africa, **Angola** is dominated by Miombo woodlands, which are among the most extensive tropical dry forests in the region, interspersed with savannas and gallery forests, and are of critical importance for biodiversity and carbon storage (Frost, 1996; Chidumayo & Gumbo, 2010). **Mozambique** shares similar

ecological features, with extensive Miombo woodlands, coastal mangroves, and evergreen forests in highland regions. **Guinea-Bissau**, although smaller in area, holds mangrove ecosystems along its coastal zones, as well as dry forests and savanna woodlands. **Cape Verde**, an archipelago with semi-arid conditions, has limited natural forests, but reforestation efforts have expanded areas of dry tropical woodlands and exotic plantations (Duarte & Romeiras, 2009). **São Tomé and Príncipe**, on the other hand, is characterised by lush tropical rainforests, cloud forests, and mangroves, reflecting its humid equatorial climate and high levels of endemism (Jones, Burlison & Tye, 1991).

In South America, **Brazil** is ecologically the most diverse Lusophone country, comprising the Amazon rainforest (largest tropical rainforest in the world) alongside the Cerrado savannas, the Atlantic Forest, the Caatinga dry forests, and the Pantanal wetlands (Myers et al., 2000; Ferreira et al., 2020). These ecosystems represent a global hotspot of biodiversity and play a central role in regulating regional and global climate systems.

In Europe, **Portugal** is characterised by Mediterranean forests, woodlands, and scrublands, particularly cork oak (*Quercus suber*) and holm oak (*Quercus rotundifolia*) montados, as well as pine and eucalyptus plantations, which have expanded significantly in the past decades (Costa et al., 2011).

In Asia, **Timor-Leste** is home to tropical moist deciduous and evergreen forests, monsoon forests, and coastal mangroves, though these ecosystems have experienced pressures from shifting cultivation and deforestation (Trainor, 2007).

In Asia, **China** stands out for its vast ecological diversity, ranging from boreal forests in the northeast to subtropical evergreen broadleaf forests in the south, as well as extensive temperate deciduous and mixed forests across central regions (Song & Zhang, 2019). These ecosystems have been subject to intense anthropogenic pressures, including deforestation and land-use change, but also to large-scale reforestation and afforestation initiatives such as the “Grain for Green” programme, which have significantly altered forest cover and carbon dynamics in recent decades (Fang et al., 2018). Within this context, **Macau**, a Special Administrative Region with historical Portuguese influence, presents a subtropical monsoon climate and highly urbanised landscape, where natural forest cover is limited to small patches of secondary vegetation and coastal green spaces (Zhang et al., 2021). Despite its small size, Macau serves as an important cultural and geopolitical bridge between China and the Lusophone world, making its inclusion in this comparative analysis particularly relevant.

Together, these countries form a network of forest ecosystems that span a wide range of biomes, from humid tropical rainforests to semi-arid woodlands and Mediterranean systems. This ecological diversity reflects the global reach of

Lusophone countries and highlights their importance for biodiversity conservation, carbon sequestration, and socio-ecological resilience.

## ***2.2. Data and methodology***

Forest cover and CO<sub>2</sub> emissions data were primarily obtained from GFW, which incorporates the widely adopted Hansen GFC v1.12 dataset (Hansen et al., 2013). This dataset provides global, wall-to-wall information at 30 m spatial resolution, derived from multi-temporal Landsat imagery. It delivers annual metrics of forest extent, loss, and gain, thereby enabling robust monitoring of spatio-temporal changes. The GFW platform applies consistent algorithms across countries, ensuring methodological comparability and harmonisation in cross-country analyses.

To reinforce the robustness of the results, EarthMap (Food and Agriculture Organization of the United Nations/Google) was employed as a complementary tool for interactive visualisation and validation of forest change patterns. EarthMap integrates multiple global datasets (e.g., biomass, land cover, climate indicators) at varying spatial resolutions, which facilitates contextual interpretation of deforestation drivers and enhances transparency of forest monitoring efforts.

In terms of RS processing, forest cover mapping and temporal analysis were conducted using GEE, a cloud-based geospatial processing platform designed for large-scale Earth observation analytics. The Hansen GFC v1.12 dataset (2000–2024) was accessed via GEE, allowing systematic processing of dataset using GC Pro. The methodology included: (i) Annual forest cover assessment: Derivation of forest extent per country, expressed in hectares and as a percentage of total land area; (ii) Forest loss and gain dynamics: Calculation of annual deforestation and regeneration rates, including cumulative trends over the 2001–2024 period; (iii) Spatial pattern analysis: Mapping of hotspots of deforestation and reforestation at subnational scales, enabling the identification of geographically concentrated processes.

Associated CO<sub>2</sub> emissions were quantified using GFW's emissions dataset, which couples remotely sensed forest loss with biomass carbon density estimates. Emissions calculations are based on IPCC Tier 1 methodologies, drawing on globally consistent datasets of aboveground biomass stocks and carbon fraction conversion factors. For each country, forest loss events were translated into CO<sub>2</sub> emissions, expressed in absolute terms (MtCO<sub>2</sub>/year) and normalised by forest area (tCO<sub>2</sub>/ha/year). This normalisation facilitated direct comparison across countries of vastly different sizes, from small island states such as São Tomé and Príncipe to continental-scale Brazil and China.

To systematically contrast forest cover dynamics and CO<sub>2</sub> emissions between Portuguese-speaking countries and China, a multi-dimensional comparative framework was developed: (i) Temporal trend analysis (2001–2024): Country-level time series were generated for forest extent, annual forest loss, forest gain, and CO<sub>2</sub> emissions. Trend lines were smoothed using rolling averages to highlight structural changes rather than short-term fluctuations; (ii) Cross-country comparative assessment: Indicators of forest loss rates and CO<sub>2</sub> emissions intensity were compared across the Lusophone group and China. Both absolute and relative values were analysed to account for differences in land area and forest baselines; (iii) Explanatory factor integration: Socio-economic and environmental variables (e.g., population growth, Gross domestic product per capita, agricultural expansion, logging concessions, and protected area coverage) were qualitatively integrated through literature review and ancillary datasets, enabling interpretation of the observed divergences.

### ***2.3. Data analysis and visualisation***

The processed data were exported from GEE and GFW and further analysed in GC pro (Python environment), ensuring open-source reproducibility and transparent workflows. The analysis pipeline included: (i) Data wrangling: Tabular processing with *Pandas* to structure multi-country time series; (ii) Spatial analysis: Use of *GeoPandas* and *Shapely* for country-level overlays and aggregation of spatial units; (iii) Statistical analysis: Application of descriptive statistics and correlation tests to explore association between forest cover change and CO<sub>2</sub> emissions; (iv) Visualisation: Generation of comparative line charts, bar graphs, and geospatial heatmaps using *Matplotlib* and *Seaborn*. Visual outputs emphasised temporal dynamics, cross-country differences, and emission hotspots.

The methodological workflow therefore combined high-resolution RS data, cloud-based geospatial analysis, and reproducible open-source data science practices to deliver a robust comparative assessment of forest cover change and CO<sub>2</sub> emissions in Portuguese-speaking countries and China.

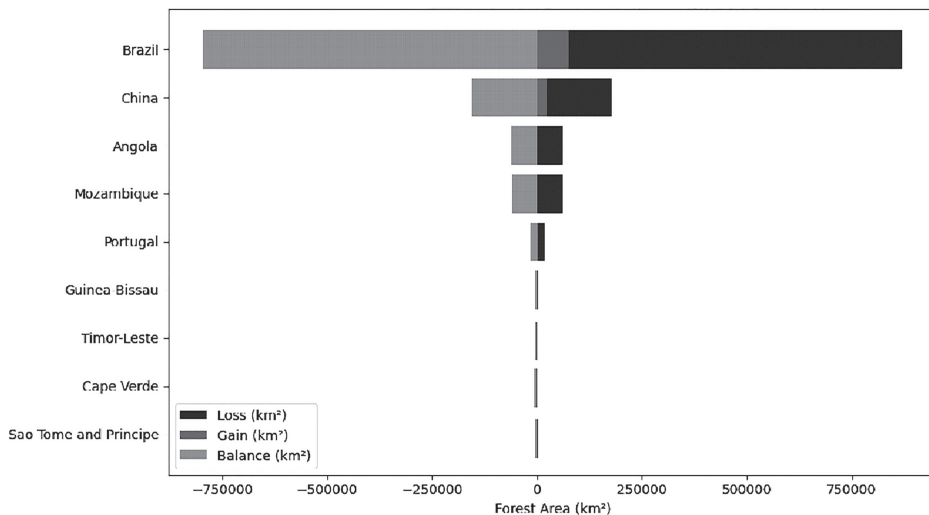
## **3. Results**

### ***3.1. Spatial and temporal variation of forest cover in Portuguese-speaking countries and China***

The assessment of forest cover dynamics between 2001 and 2024 among Portuguese-speaking countries and China, using Hansen's Landsat dataset, highlights a strong spatial imbalance in forest change patterns. Brazil alone accounts for nearly 82% of total forest loss and about 96% of total forest gain

across all assessed countries, confirming its central role in global forest carbon dynamics. China follows with approximately 17% of total forest loss and 3% of forest gain, reflecting its large-scale reforestation programmes that partially offset continued deforestation in some regions. In contrast, Angola and Mozambique represent around 7% of total forest loss combined, both showing clear signs of land-use expansion and fire-related degradation. See figure 2.

**Figure 2.** Forest Cover Dynamics (2001–2024) in Portuguese-speaking Countries and China.



On the other end of the spectrum, small island nations such as São Tomé and Príncipe and Cabo Verde, along with Timor-Leste, contribute less than 0.01% of the overall changes. Their small territorial size and limited forest area explain these minimal variations. Portugal presents a moderate case, with forest losses around 2% of the total, largely associated with wildfires and changes in plantation management.

Overall, these proportions confirm that large tropical and subtropical countries (particularly Brazil, China, Angola, and Mozambique) dominate the regional forest carbon balance, while smaller Lusophone nations show negligible impact on global forest cover trends

### 3.2. CO<sub>2</sub> emissions related to forest cover changes

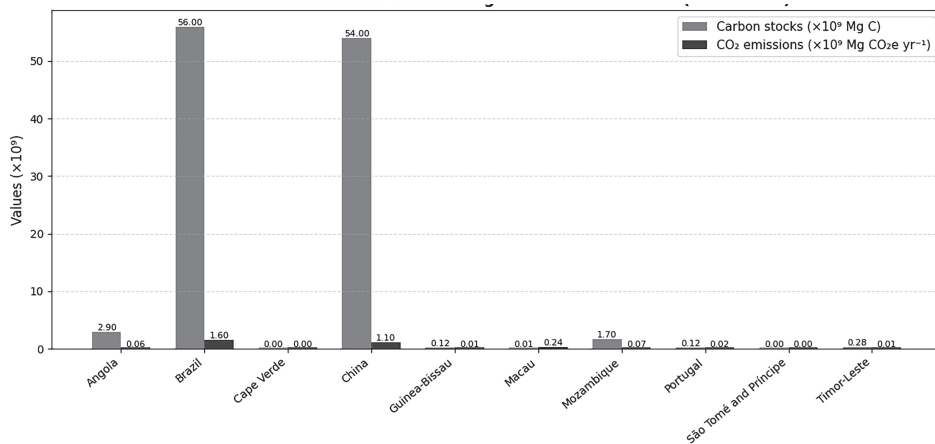
The comparative analysis reveals significant disparities in forest carbon dynamics among Portuguese-speaking countries and China between 2001 and 2024. Brazil clearly stands out as the dominant contributor, possessing by far the largest aboveground carbon stock (exceeding  $50 \times 10^9$  Mg C) as well as the highest

gross CO<sub>2</sub> emissions related to forest cover loss, with annual values approaching  $1.6 \times 10^9$  Mg CO<sub>2</sub>e. These figures reflect Brazil’s vast forest area, particularly the Amazon biome, which plays a pivotal role in the global carbon cycle but also faces persistent deforestation pressures. See figure 3.

China follows as the second-largest country in terms of both carbon stocks and CO<sub>2</sub> emissions. Although its total carbon stock is comparable to Brazil’s, the emissions are slightly lower, suggesting a more effective implementation of large-scale reforestation and forest management programmes in recent years.

Among African Lusophone countries, Angola and Mozambique display similar patterns, with substantial carbon stocks (around  $2\text{--}3 \times 10^9$  Mg C) and moderate annual CO<sub>2</sub> emissions (approximately  $6 \times 10^7$  Mg CO<sub>2</sub>e yr<sup>-1</sup>). These levels indicate that both nations maintain considerable forest resources, mainly within Miombo woodlands, but are also experiencing measurable losses linked to agricultural expansion, charcoal production, and fire activity.

**Figure 3.** Forest CO<sub>2</sub> Emissions and Aboveground Carbon Stocks (2001–2024) in Lusophone countries.



Portugal and Timor-Leste occupy an intermediate position. Their carbon stocks are lower compared with tropical countries, yet both exhibit non-negligible emissions due to forest fires and land-use changes. In contrast, smaller island nations—such as São Tomé and Príncipe, Cape Verde, and Guinea-Bissau—hold limited forested areas, resulting in relatively low carbon stocks (below  $0.2 \times 10^9$  Mg C) and negligible CO<sub>2</sub> emissions.

Macau’s values are distinctively high relative to its small geographic size, which is likely a result of dataset generalisation or inclusion within the broader Pearl River Delta region of southern China.

Building on this, the comparative summary of forest carbon and CO<sub>2</sub> fluxes (2001-2024), in table 1, reinforces the disproportionate role of large tropical and subtropical nations in the global carbon cycle.

**Table 1.** Comparative data of Forest Carbon and CO<sub>2</sub> Fluxes (2001–2024) in Lusophone countries.

Country	Aboveground Carbon Stocks 2000 (Mg C)	% of Total Carbon Stock	Gross CO <sub>2</sub> Emissions (Mg CO <sub>2</sub> e yr <sup>-1</sup> )	% of Total Emissions
Angola	$2.9 \times 10^9$	2.63 %	$5.9 \times 10^7$	2.49 %
Brazil	$5.6 \times 10^{10}$	50.86 %	$1.6 \times 10^9$	67.53 %
Cape Verde	$1.0 \times 10^6$	0.00 %	$2.0 \times 10^5$	0.01 %
China	$5.4 \times 10^{10}$	49.06 %	$1.1 \times 10^9$	46.44 %
Guinea-Bissau	$1.2 \times 10^8$	0.11 %	$5.0 \times 10^6$	0.21 %
Macau	$1.0 \times 10^7$	0.01 %	$2.4 \times 10^8$	10.13 %
Mozambique	$1.7 \times 10^9$	1.54 %	$6.7 \times 10^7$	2.83 %
Portugal	$1.2 \times 10^8$	0.11 %	$1.7 \times 10^7$	0.72 %
São Tomé and Príncipe	$1.7 \times 10^6$	0.00 %	$2.0 \times 10^3$	0.00 %
Timor-Leste	$2.8 \times 10^8$	0.25 %	$6.0 \times 10^6$	0.25 %

Brazil and China together account for nearly 99% of the total aboveground carbon stocks among the countries assessed, and for over 80% of total CO<sub>2</sub> emissions related to forest cover change. This dominance illustrates the dual nature of their forest systems, acting simultaneously as immense carbon reservoirs and major emission sources when disturbed. Angola and Mozambique show intermediate contributions, reflecting ongoing land-use transitions such as agricultural expansion and charcoal production that continue to release stored carbon. Meanwhile, smaller island states like São Tomé and Príncipe or Cabo Verde contribute marginally to total emissions yet retain locally significant carbon densities, underscoring the importance of conserving their remaining forest fragments. The table therefore captures the contrasting scales of forest-carbon dynamics across Lusophone and partner countries, where the interplay between forest extent, land-use pressure, and emission intensity defines each nation's position in the global mitigation landscape.

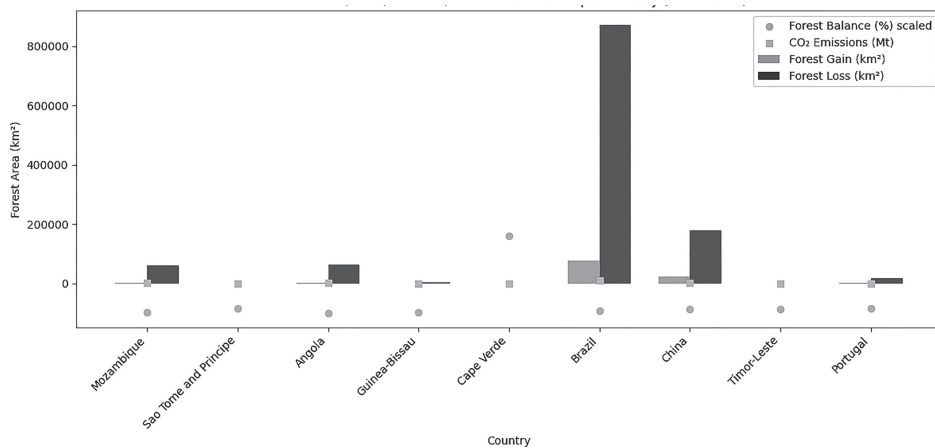
### ***3.3. Patterns and trends of forest change and CO<sub>2</sub> emissions***

China, although experiencing significant forest losses (~17% of the total), demonstrates extensive reforestation and afforestation programmes that partially

offset its emissions, illustrating a transition towards a net forest recovery trend. In sub-Saharan Africa, Angola and Mozambique contribute together nearly 7% of total forest loss, driven by fuelwood extraction, slash-and-burn agriculture, and recurring wildfires, which collectively release hundreds of millions of tonnes of CO<sub>2</sub> into the atmosphere.

In contrast, small island nations such as Cape Verde, São Tomé and Príncipe, and Timor-Leste show negligible forest change (<0.01% of total), yet their stable carbon profiles highlight the ecological value of their limited but resilient forest ecosystems. Portugal, with moderate forest losses (~2% of total), reflects a Mediterranean dynamic where frequent wildfires and changes in plantation management contribute to localised CO<sub>2</sub> emissions.

**Figure 4.** Patterns and Trends of Forest Change and CO<sub>2</sub> Emissions (2001–2024) in Lusophone countries.



Overall, these findings indicate that tropical and subtropical countries dominate the carbon fluxes of the Lusophone and Asian regions, underscoring the urgent need for integrated forest governance, reforestation incentives, and emission monitoring systems. Strengthening these mechanisms is essential to balance carbon storage and release, ensuring long-term climate stability and forest resilience in the face of socio-economic pressures and global climate change.

## 4. Discussion

### 4.1. Spatial and temporal variation of forest cover

The spatial and temporal analysis of forest cover reveals distinct regional trajectories in forest dynamics, reflecting the interplay between biophysical conditions, socio-economic development, and governance frameworks. Landsat-

derived GFC provides a consistent and long-term perspective that allows for the quantification of both forest loss and gain, shedding light on broader land-use transitions and carbon cycle implications.

Brazil dominates the overall forest dynamics, accounting for the majority of both forest loss and gain within the group. Despite substantial reforestation and natural regeneration in parts of the Amazon and the Atlantic Forest, the net balance remains negative, consistent with findings by Harris et al. (2021), who reported that Brazil contributed over one-third of global CO<sub>2</sub> emissions from forest loss between 2001 and 2019. These emissions are closely linked to agricultural expansion, pasture establishment, and periodic fire events, which collectively undermine carbon storage capacity.

China, in contrast, presents a more complex pattern characterised by simultaneous gains and losses. Large-scale afforestation and reforestation initiatives under the “Grain for Green” and “Three-North Shelterbelt” programmes have expanded forest area significantly, offsetting earlier degradation (Liu et al., 2023). However, pressures from urbanisation, infrastructure, and timber harvesting still contribute to forest loss in specific provinces, indicating that forest transitions remain uneven across space and time.

In sub-Saharan Africa, Angola and Mozambique show moderate but increasing forest loss, primarily associated with smallholder agriculture, charcoal production, and fire disturbance. These patterns align with the trends reported by Grace et al. (2014), who found that tropical dry forests and woodlands are shifting from being net carbon sinks to net carbon sources due to anthropogenic pressures and recurring drought stress. Although some regrowth is evident, it is insufficient to compensate for widespread clearing.

Smaller Lusophone countries, such as Guinea-Bissau, São Tomé and Príncipe, Cape Verde, and Timor-Leste, display much lower rates of change. Their limited land area, lower population density, and subsistence-based economies help stabilise forest cover, though localised degradation may occur due to shifting cultivation or fuelwood extraction. In Portugal, a different dynamic emerges: periodic forest loss results from extensive wildfires, plantation cycles, and changes in forest management practices typical of Mediterranean environments (San-Miguel-Ayanz et al., 2020).

The results demonstrate that tropical and subtropical nations play a decisive role in shaping the global forest balance. Their large forested areas and active land-use frontiers drive both carbon sequestration and emission dynamics. By contrast, smaller nations contribute minimally to global forest cover change but can serve as valuable case studies for sustainable forest management at smaller scales.

The observed trends emphasise that while reforestation and restoration efforts can partially offset forest losses, the persistence of deforestation, fire, and agricultural expansion continues to undermine long-term forest stability. Strengthening land-use governance, promoting sustainable agricultural systems, and integrating carbon monitoring frameworks are therefore essential to ensuring that forest resources contribute effectively to climate change mitigation.

#### ***4.2. CO<sub>2</sub> emissions and forest cover changes***

The comparative results reveal a strong association between aboveground forest carbon stocks and CO<sub>2</sub> emissions from forest cover changes across countries in study. This pattern reinforces evidence that deforestation and forest degradation are major global drivers of carbon emissions and climate forcing (Harris et al., 2021; Hansen et al., 2013; Tyukavina et al., 2022).

Deforestation, land conversion, and wildfires are among the key processes responsible for tree-cover loss and the release of stored biomass carbon (Toleva et al., 2025). Countries with large forest carbon reservoirs (such as Brazil, China, and Angola) also record higher gross emissions, reflecting the direct link between the scale of forest resources and potential carbon losses. As Baccini et al. (2012) and Houghton et al. (2012) demonstrated, when extensive, carbon-rich forests are disturbed or cleared, the stored carbon is released rapidly into the atmosphere.

Recent studies suggest that tropical forests are increasingly shifting from carbon sinks to carbon sources due to escalating disturbance pressures (Qian et al., 2025). This reinforces the need for stronger forest governance, as even small losses in high-carbon ecosystems can undermine national mitigation targets. In Brazil, for example, large emissions persist despite declining deforestation rates, simply because of the vast biomass stock involved (Basso et al., 2023). Similarly, in Angola and Mozambique, moderate to high carbon stocks coincide with measurable emissions linked to agricultural expansion, charcoal production, and shifting cultivation. São Tomé and Príncipe exhibits much lower total emissions, yet their high carbon density underscores the disproportionate value of conserving remaining forest fragments.

China provides a distinctive case: while historical deforestation contributed to large legacy emissions, recent large-scale afforestation programmes have partially offset losses (Harris et al., 2021). Nevertheless, as Smith et al. (2016) note, the persistence of emissions even in reforested regions reflects the difficulty of restoring the original carbon equilibrium once mature forests are lost.

Overall, the analysis shows that high carbon stocks alone do not ensure low emissions; the net carbon outcome depends on the balance between forest retention, disturbance, and regrowth. As Scheinkman (2024) and Le Quéré

et al. (2018) emphasize, economic and policy instruments (carbon pricing, REDD+ mechanisms, and sustainable land-use zoning) can effectively promote conservation and regeneration in regions under high forest pressure.

These findings confirm that protecting forest carbon stocks and limiting forest loss are both essential for climate mitigation. Even forests with large carbon reservoirs can become net emitters if disturbances increase, highlighting the need for strong policies, monitoring, and incentives to maintain the global forest carbon balance.

#### ***4.3. Forest change patterns/trends and CO<sub>2</sub> emissions***

The patterns of forest change and CO<sub>2</sub> emissions reveal marked regional disparities, reflecting differences in land-use dynamics and governance. Brazil is the main contributor to forest loss and carbon emissions in the group, accounting for over 80% of total forest loss and nearly 8.7 billion tonnes of CO<sub>2</sub> in study period. As Harris et al. (2021) show, deforestation in tropical biomes (particularly the Amazon) remains the largest single source of land-use-related CO<sub>2</sub> emissions, primarily driven by agricultural expansion and pasture conversion.

China, despite significant forest losses, shows a contrasting trend through widespread reforestation and afforestation. Liu et al. (2023) note that large-scale tree-planting initiatives have converted several provinces into emerging carbon sinks, partially offsetting historical degradation. Nevertheless, ongoing urban expansion and plantation turnover continue to produce substantial emissions, highlighting the challenge of balancing economic growth with carbon neutrality goals.

In sub-Saharan Africa, Angola and Mozambique exhibit intermediate forest loss and related emissions, primarily driven by shifting cultivation, fuelwood extraction, and fire disturbance, which erode carbon stocks and forest resilience. Grace et al. (2014) showed that such land-use pressures are increasingly converting formerly stable African tropical woodlands from carbon sinks into net CO<sub>2</sub> sources, consistent with the patterns observed here.

Conversely, smaller island nations (São Tomé and Príncipe, Cape Verde, and Timor-Leste) show minimal forest change and low emissions, reflecting their limited land area and relatively stable vegetation. Portugal, though outside the tropics, generates moderate emissions, primarily from recurring wildfires and plantation dynamics characteristic of Mediterranean ecosystems.

Overall, these results support the consensus that tropical and subtropical regions disproportionately influence global carbon cycling. Strengthening forest protection, promoting community-based reforestation, and implementing

transparent emission monitoring are essential for advancing carbon neutrality and climate resilience across the study countries.

#### ***4.4. Methodological limitations of this study***

While this study provides a comprehensive assessment of forest cover dynamics and CO<sub>2</sub> emissions across study countries, several methodological limitations warrant consideration. First, the use of IPCC Tier-1 emission factors introduces inherent uncertainty, as these default values may not capture region-specific variations in forest carbon density and emission characteristics. Second, the spatial generalisation of datasets affects accuracy in small or complex regions, notably Macau, where emissions and carbon stocks may be overestimated due to aggregation within broader administrative units. Third, the analysis does not distinguish between natural and planted forests, limiting the ability to assess differences in carbon sequestration potential and ecological function across forest types. Finally, the study relies on aggregated national data, which constrains interpretation at finer spatial scales and may obscure sub-national variability, degradation dynamics, and specific land-use transitions (Ahmad et al., 2022).

These limitations highlight avenues for future research. The development of higher-tier, regionally tailored emission factors would reduce uncertainty in carbon estimates. The use of higher-resolution spatial datasets (e.g., Sentinel-2 at 10 m) could improve accuracy in small or complex regions such as Macau. Including additional normalized indicators, such as emissions per remaining forest area, would enhance comparability across countries, particularly for smaller nations like São Tomé and Príncipe, Cape Verde, and Timor-Leste, which currently appear marginal in aggregated analyses. Finally, quantitative integration of socio-economic and management drivers (land-use policies, agricultural expansion, and fire regimes) would provide a more precise understanding of their influence on forest-carbon dynamics. Addressing these aspects in future studies will strengthen carbon flux assessments and support more effective forest management and climate mitigation strategies.

### **5. Conclusion**

Between 2001 and 2024, forest cover in Portuguese-speaking countries and China showed clear spatial contrasts. Brazil and China dominated both forest loss and gain, reflecting their vast forest areas and differing land-use trajectories, while Angola and Mozambique experienced notable deforestation, and smaller island nations remained largely stable.

Brazil and China were responsible for over 80% of total CO<sub>2</sub> emissions linked to forest loss, highlighting their central role in global carbon dynamics. African

Lusophone countries contributed moderate emissions from Miombo degradation, whereas island states showed negligible impacts.

Contrasting trends reveal that China is progressing toward net forest recovery through reforestation, while Brazil, Angola, and Mozambique continue to face significant deforestation pressures.

Recommendation: Strengthen integrated forest governance, REDD+ implementation, and community-based reforestation (particularly in Angola, Mozambique, and Brazil) to reduce emissions and enhance carbon resilience.

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