**DECOUPLED TRAJECTORIES: FOSSIL CO₂ INTENSITY, LAND-USE EMISSIONS, AND FOREST DYNAMICS IN SOUTH AMERICA (2000–2020)**

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# Abstract

South America combines extensive tropical forests and large land‑use carbon stocks with an energy system that is relatively low in fossil CO₂ intensity, due in part to widespread use of hydropower. Conventional indicators of climate performance, such as fossil CO₂ emissions per unit of GDP at purchasing power parity, therefore capture only part of the region’s greenhouse gas dynamics and risk overlooking land‑use, land‑use change and forestry (LULUCF) emissions. This article examines how forest area, fossil CO₂ intensity of GDP, LULUCF emissions and the electricity mix co‑evolved in twelve South American countries between 2000 and 2020. Using harmonised country–year data from regional and international statistical agencies, we construct a small panel for 2000, 2010 and 2020, derive decadal changes for 2000–2010 and 2010–2020, and estimate linear regressions that relate decadal changes in fossil CO₂ intensity and in per‑capita LULUCF emissions to changes in forest area, the hydropower share of electricity generation, GDP per capita and the agriculture value added share of GDP. The analysis shows that fossil CO₂ emissions per unit of GDP declined in most countries and that these reductions are significantly associated with increases in the hydropower share and with gains in GDP per capita, whereas decadal percentage changes in forest area are not significantly associated with changes in fossil CO₂ intensity once energy and income dynamics are taken into account. In contrast, decadal changes in per‑capita LULUCF emissions are closely associated with forest area dynamics and with changes in the agriculture share of GDP: greater forest loss is linked to larger increases in per‑capita LULUCF emissions, while declines in the agriculture share of GDP are associated with more favourable LULUCF trajectories. Simple regional groupings of countries show that low or declining fossil CO₂ intensity of GDP can coexist with continued forest loss. Taken together, the results indicate that energy‑sector decarbonisation and land‑use emissions follow distinct, though interconnected, trajectories in South America and that assessments of climate performance that rely solely on fossil CO₂ intensity of GDP may overstate mitigation progress in forest‑rich economies.

**Keywords**: South America; deforestation; land‑use, land‑use change and forestry (LULUCF); fossil CO₂ intensity of GDP; hydropower; electricity mix; agricultural structure; Sustainable Development Goals.

#### Highlights

* Fossil CO₂ intensity of GDP in South America declined mainly with changes in the electricity mix and income, not with decadal changes in forest area.
* Per‑capita LULUCF emission changes are closely linked to forest loss and to shifts in agriculture’s share of GDP.
* Regional country clusters show that low or declining fossil CO₂ intensity can coexist with substantial or mixed forest trends.
* Standard climate indicators based only on fossil CO₂ intensity may overstate mitigation progress in forest‑rich economies where land‑use emissions remain high.
* Mitigation strategies in South America need to integrate clean energy transitions, forest conservation and agricultural development in line with the Sustainable Development Goals.

# Introduction

South America occupies a distinctive position in the global climate system. The region hosts some of the world’s largest remaining tropical forests and associated carbon stocks, while at the same time supplying land‑intensive commodities such as soybeans, beef and minerals to global markets. Over the past two decades, South American economies have navigated periods of rapid commodity‑driven growth and subsequent slowdowns, during which the tension between conserving forest ecosystems and expanding export‑oriented production has become increasingly visible. This tension is particularly pronounced in countries where forest‑rich biomes underpin both biodiversity and hydrological regulation, and where land‑use change and forestry still account for a substantial share of total greenhouse gas emissions (Carter et al., 2018; Nyawira et al., 2024).

Conventional indicators used to track climate performance typically focus on fossil CO₂ emissions and their relationship to economic output. A widely used example is the indicator of fossil CO₂ emissions per unit of GDP at purchasing power parity, which is reported by CEPALSTAT and other agencies for South American countries and interpreted as a measure of the carbon intensity of economic activity (Peng et al., 2024). Such indicators are informative about energy‑sector decarbonisation, especially in regions where electricity generation is dominated by fossil fuels. However, in South America, where hydropower and other low‑carbon sources play a central role in many national electricity systems, and where land‑use, land‑use change and forestry (LULUCF) emissions are large, focusing exclusively on fossil CO₂ intensity creates a potential blind spot. Countries can appear to decarbonise their economies when measured by fossil CO₂ intensity of GDP, even as forest loss and associated land‑use emissions continue.

At the same time, land‑use dynamics in South America are shaped by a complex interplay of domestic policies, global demand and structural economic change. Research on global economic and diet transitions shows that shifting consumption patterns and external demand for agricultural commodities have contributed to forest loss in Latin America and the Caribbean (López‑Carr et al., 2022). Studies of land‑use change and emissions in Brazil and other countries in the region highlight the central role of agriculture‑driven deforestation, cattle production and commodity frontiers in explaining national LULUCF trajectories (Rodrigues et al., 2023; Sandoval & Burkart, 2023; Sanquetta et al., 2020). Scenario‑based analyses of Brazil’s Forest Code and national mitigation pathways show that legal frameworks, enforcement and land‑use policies can significantly alter future emission trajectories and trade‑offs between agricultural production and environmental conservation (Köberle et al., 2020; Soterroni et al., 2018; Wiltshire et al., 2022). Against this background, understanding how forest change, land‑use emissions and energy‑related emissions co‑evolve at the national level is a prerequisite for designing effective and coherent mitigation strategies in South America.

An additional dimension arises from the interaction between forests, the hydrological cycle and hydropower‑dependent energy systems. Several South American countries rely heavily on hydropower for electricity generation, and changes in precipitation patterns and river flows have direct implications for energy security and decarbonisation pathways. Studies of the 2015–2016 megadrought in Colombia, for example, show how extreme drought events can stress hydropower systems and catalyse adjustments in the energy mix (Weng et al., 2020). Research on trade‑offs and synergies between climate mitigation, biodiversity conservation and agro‑economic development in Brazil, as well as on land conservation and the renewable energy transition, points to the need to consider water, energy, land and biodiversity jointly when evaluating mitigation options (Gérard et al., 2025; Borba et al., 2024). In this context, large‑scale forest loss in South America is not only a source of land‑use emissions, but may also affect the hydrological foundations of hydropower and, indirectly, the prospects for maintaining low‑carbon electricity systems.

Despite this interconnectedness, national and regional assessments often treat energy‑related emissions and land‑use emissions separately. Energy‑system analyses emphasise the role of renewable energy deployment, technological innovation and structural change in reducing fossil CO₂ emissions per unit of output (Machado et al., 2020; Raihan, 2023), while land‑use studies focus on deforestation, agricultural expansion and associated LULUCF emissions (Carter et al., 2018; Nyawira et al., 2024; Roman‑Cuesta et al., 2016). Emission accounting and driver studies for South American countries demonstrate that both components are important for national greenhouse gas profiles (Peng et al., 2024), but systematic analyses that examine how forest area, LULUCF emissions, energy mixes and fossil CO₂ intensity of GDP co‑evolve across countries and over time remain relatively scarce. This gap is particularly relevant for South America, where many countries report relatively low fossil CO₂ intensity of GDP compared to other regions, while still experiencing substantial forest loss and land‑use change.

This article addresses this gap by analysing the co‑evolution of forest area, fossil CO₂ intensity of GDP, LULUCF emissions and the electricity mix in twelve South American countries—Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay and Venezuela—over the period 2000–2020. Using harmonised country–year data from CEPALSTAT, the World Bank and FAOSTAT, we construct a small panel with three benchmark years (2000, 2010 and 2020) and define decadal changes for two intervals (2000–2010 and 2010–2020). We then relate decadal changes in fossil CO₂ intensity of GDP to changes in forest area, the hydropower share of electricity generation and GDP per capita, and decadal changes in per‑capita LULUCF emissions to changes in forest area and the agriculture value added share of GDP. In addition, we use simple regional groupings of countries to highlight how these relationships play out across different structural contexts, including agricultural Southern Cone economies and Andean and Amazon‑frontier countries.

The study contributes to the literature in three main ways. First, it provides a comparative, region‑wide assessment of how fossil CO₂ intensity of GDP and per‑capita LULUCF emissions evolve in parallel in South America, and how they relate to changes in forest area, energy mixes and economic structure. Second, it illustrates empirically how reliance on fossil CO₂ intensity of GDP as a sole indicator of climate performance can obscure ongoing land‑use emissions in forest‑rich economies, thereby underscoring the importance of integrating land‑use emissions into assessments of mitigation progress. Third, it situates these empirical findings within the broader context of the Sustainable Development Goals, particularly SDG 7 (affordable and clean energy), SDG 13 (climate action) and SDG 15 (life on land), and it points to tensions and potential synergies with SDG 2 (zero hunger) and SDG 16 (peace, justice and strong institutions).

The remainder of the article is organised as follows. The Methods section describes the construction of the country–year and decadal‑change panels, the variables used and the regression models. The Results section presents descriptive patterns and regression findings for fossil CO₂ intensity of GDP, per‑capita LULUCF emissions and the electricity mix. The Discussion interprets these findings in light of existing literature and the Sustainable Development Goals, and identifies limitations and priorities for future research. The Conclusion summarises the main messages and outlines implications for climate and land‑use policy in South America.

# Methods

This study uses an observational, comparative country-level design to examine how changes in forest area, land‑use emissions and the energy system relate to the fossil CO₂ intensity of gross domestic product in South America. The empirical strategy combines harmonised official statistics for twelve countries with a simple decadal‑change framework and linear regression models. The analysis is framed in relation to the Sustainable Development Goals, in particular goals on affordable and clean energy, climate action, life on land, food systems and institutions.

The study area comprises twelve South American countries, identified by their ISO3 codes: Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay and Venezuela. National territories and population counts follow the definitions used by the data providers. The temporal scope is restricted to three benchmark years, 2000, 2010 and 2020, which offer sufficiently consistent coverage across data sources. Decadal changes are defined over the 2000–2010 and 2010–2020 intervals. The resulting analysis panel contains thirty‑six country–year observations in levels and twenty‑four country–period observations in decadal differences.

## Data sources and indicators

We construct a harmonised country–year panel by combining data from CEPALSTAT, the World Bank’s World Development Indicators and FAOSTAT. All variables are aggregated to the national level and aligned on a common calendar‑year basis. Where original series are provided in alternative units, we standardise them to physically interpretable units such as thousand hectares, tonnes of CO₂ equivalent, kilograms of CO₂ per unit of output, or population‑weighted rates.

From CEPALSTAT we obtain forest area, fossil CO₂ emissions per unit of gross domestic product at purchasing power parity, the share of agriculture in value added, the share of terrestrial and marine protected areas, the Gini index and the incidence of rural extreme poverty. Forest area is measured as total forest area per country in thousand hectares. Fossil CO₂ intensity of GDP is expressed as kilograms of CO₂ per constant 2017 international‑dollar of GDP in purchasing power parity terms, which is a standard indicator of energy‑related emission intensity. The agriculture value added share of GDP is used as a proxy for structural change in the economy. The protected areas share, the Gini index and rural extreme poverty serve as contextual variables and potential controls for social and institutional conditions where data are available.

World Bank World Development Indicators provide information on the energy system, macroeconomic structure, and governance. We use the percentage shares of electricity generated from hydropower, coal, natural gas, and non‑hydropower renewables, as well as the share of the population with access to electricity. Economic indicators include GDP per capita in constant 2017 international‑dollars at purchasing power parity, total GDP in constant 2015 US‑dollars and the percentage of GDP accounted for by oil rents. Demographic indicators comprise total population and population density. To characterise institutional quality, we draw on the Worldwide Governance Indicators for control of corruption and rule of law, which are available for most years in the study period.

Land‑use, agricultural and land‑use emissions data are taken from FAOSTAT bulk downloads in normalised format. We use crop and land‑use datasets to derive national time series for harvested area under soybeans, harvested area under sugarcane and permanent meadows and pastures. These areas are measured in hectares and converted to thousand‑hectare units for consistency with forest area. We combine fertiliser input data to obtain nitrogen fertiliser application rates in kilograms per hectare of agricultural land. From the FAOSTAT emissions totals dataset we extract total land‑use, land‑use change and forestry emissions, expressed as thousand tonnes of CO₂ equivalent based on the AR5 global warming potentials. These LULUCF totals form the basis for per‑capita land‑use emissions and their decadal changes.

CEPALSTAT and World Bank series are retrieved programmatically through their public application programming interfaces using dedicated Python clients. The clients query the indicator‑specific endpoints, request English‑language output in JSON format, and parse the resulting data cubes into tidy tabular structures with explicit country, year and indicator dimensions. FAOSTAT bulk files are downloaded once, stored locally, decompressed and read as comma‑separated values. For FAOSTAT we rely on the normalised format, which provides a stable layout of area, item and element codes across datasets and facilitates consistent filtering for the specific crops, land‑use categories and emission elements relevant to this study.

To support transparent reporting of the empirical design, all variables, units, transformations and data sources used in the analysis panels are summarised in a separate codebook. The codebook is linked to the master analysis panel and to the scripts that construct each derived variable.

**Table 1. Overview of variables, data sources and units**

| Variable | Source | Unit |
| --- | --- | --- |
| Country ISO3 code | Multiple (CEPALSTAT, FAOSTAT, World Bank) | - |
| Calendar year | Multiple | year |
| Forest area | CEPALSTAT indicator 2036 | thousand hectares |
| CO2 emissions per unit of GDP PPP (constant 2017 USD) | CEPALSTAT indicator 3914 | kg CO2 / USD |
| Agriculture value added as share of GDP | CEPALSTAT indicator 3745 | percent |
| GDP per capita, PPP (constant 2017 international dollars) | World Bank NY.GDP.PCAP.PP.KD | 2017 international USD per capita |
| Electricity production from hydroelectric sources, share of total | World Bank EG.ELC.HYRO.ZS | percent |
| Electricity production from coal sources, share of total | World Bank EG.ELC.COAL.ZS | percent |
| Electricity production from natural gas sources, share of total | World Bank EG.ELC.NGAS.ZS | percent |
| Electricity production from renewables excluding hydro, share of total | World Bank EG.ELC.RNWX.ZS | percent |
| Access to electricity, total | World Bank EG.ELC.ACCS.ZS | percent of population |
| Soy harvested area | FAOSTAT Production Crops & Livestock (Item Code 236, Element 5312) | thousand hectares |
| Sugarcane harvested area | FAOSTAT Production Crops & Livestock (Item Code 156, Element 5312) | thousand hectares |
| Permanent meadows and pastures area | FAOSTAT Inputs LandUse (Item Code 6655, Element 5110) | thousand hectares |
| Nitrogen fertilizer application rate | FAOSTAT Inputs Fertilizers by Nutrient (Item Code 3102, Element 5157) | kg nutrient per hectare |
| Total LULUCF net GHG emissions | FAOSTAT Emissions Totals (Item Code 1707, Element 723113) | kilotonnes CO2eq |
| Total population | World Bank SP.POP.TOTL | persons |
| Population density | World Bank EN.POP.DNST | people per sq. km of land area |
| Decadal percentage change in forest area | Computed from forest\_area\_kha | percent |
| Decadal absolute change in CO2 intensity per GDP | Computed from co2\_per\_gdp\_kg\_per\_usd | kg CO2 / USD |
| Decadal change in LULUCF emissions per capita | Computed from lulucf\_total\_kt\_co2eq and population\_total | tonnes CO2eq per capita |
| Decadal change in hydro electricity share | Computed from hydro\_electricity\_share\_pct | percentage points |
| Decadal change in GDP per capita PPP | Computed from gdp\_per\_capita\_ppp\_const2017 | 2017 international USD per capita |
| Decadal change in agriculture value added share of GDP | Computed from agriculture\_value\_added\_share\_gdp\_pct | percentage points |

## Data processing and construction of analysis panels

The extract–transform–load workflow is implemented as a sequence of modular Python scripts. Each script reads one or more input files, performs a clearly defined set of transformations and writes a new comma‑separated output file. This design ensures that all steps from raw data to the analysis panels are reproducible and can be re‑run if the underlying data are updated.

In a first step, we construct a basic forest–energy panel that combines total forest area and fossil CO₂ intensity of GDP from CEPALSTAT for all years with available data. Forest area and CO₂ intensity series are harmonised so that each record corresponds to a unique country–year combination. This base panel is then extended to include agriculture value added, land‑use variables derived from FAOSTAT, World Bank energy mix variables, governance indicators, social indicators and trade‑related measures. Each extension script merges its additional variables on country and year keys, checks for duplicate records and retains a single row per country–year.

The successive extensions yield a comprehensive “master” panel containing forest, energy, economic, land‑use, governance and social indicators at annual resolution. A final script adds total population and population density from the World Bank. To prepare the dataset for statistical analysis, we restrict the sample to the twelve South American countries of interest and the three benchmark years 2000, 2010 and 2020. We then generate an analysis‑ready version of the master panel by dropping variables that contain only missing values across all sample observations and by standardising variable names and units. This level panel forms the basis for descriptive statistics and visualisations.

Decadal change variables are derived from the same master panel. For each country, observations are sorted chronologically and differences between consecutive benchmark years are computed. The resulting delta panel contains one observation per country and decade, identified by the end year of the period and an indicator for the corresponding start year. As with the level panel, an analysis‑ready version of the delta panel is created by dropping variables with no non‑missing observations in the sample.

Throughout the processing pipeline we use consistent country identifiers, rely on transparent unit conversions and record all intermediate outputs on disk. No observations are imputed. Missing values in upstream sources appear as missing values in the merged panels, and statistical models are estimated on the largest subset of observations with complete data for the variables included in a given specification.

## Definition of decadal changes

Decadal changes are defined as first differences over approximately ten years. For each country, the change in a variable between 2000 and 2010 is calculated as the value in 2010 minus the value in 2000, and the change between 2010 and 2020 is calculated analogously. The resulting delta variables measure the net change over each decade rather than annual growth rates.

Forest area dynamics are captured through both absolute and relative changes. Absolute change in forest area is defined as the difference in thousand hectares between the end and start year of each decade. Percentage change in forest area is defined as the absolute change divided by the initial forest area level, multiplied by one hundred. This relative metric facilitates comparison across countries with very different forest area endowments. Changes in the fossil CO₂ intensity of GDP are measured in absolute terms as differences in kilograms of CO₂ per unit of GDP. Changes in the energy system are represented by differences in the percentage share of electricity generated from hydropower between the end and start years of each decade. This change in hydropower share reflects the contribution of hydropower expansion or contraction to the decarbonisation of the electricity mix.

Economic and structural transformation is represented by decadal changes in GDP per capita at purchasing power parity and in the agriculture value added share of GDP. The change in GDP per capita is defined in absolute terms, in constant 2017 international‑dollars, to capture the scale of income growth. The change in the agricultural share of GDP is defined in percentage points and provides a measure of structural change away from or towards agriculture. Together, these indicators characterise the joint evolution of economic development and sectoral structure.

Land‑use emissions are analysed in per‑capita terms. Total LULUCF emissions for each country and year are divided by total population to obtain per‑capita land‑use emissions in tonnes of CO₂ equivalent per person. Decadal changes in per‑capita LULUCF emissions are then defined as first differences of this per‑capita series. This construction ensures that the dependent variable in the LULUCF regressions reflects changes in land‑use emissions from the perspective of individuals while controlling for population growth. The delta panel thus includes both the level of per‑capita LULUCF emissions at the end of each decade and the change over the decade.

## Statistical analysis

The statistical analysis proceeds in two stages. In a first stage we use the level and delta panels to compute descriptive statistics and explore pairwise associations among key variables. For each benchmark year we calculate the mean, standard deviation, minimum and maximum of forest area, fossil CO₂ intensity of GDP, LULUCF emissions, selected land‑use variables such as areas under soybeans, sugarcane and pasture, fertiliser use, GDP per capita and population density. We also compute correlation matrices for selected subsets of variables to characterise simple bivariate relationships. These descriptive analyses provide context but do not identify causal effects.

In a second stage we estimate linear regression models that relate decadal changes in fossil CO₂ intensity and in LULUCF emissions per capita to changes in forests, the energy system and economic structure. The sample size for the decadal models is limited by the number of countries and the requirement that both endpoints of a decade be observed for all variables included in a specification. All models are estimated by ordinary least squares using the delta panel and are cross‑sectional in the sense that each country–decade observation contributes at most one observation to a given regression.

To analyse changes in fossil CO₂ intensity of GDP we estimate models in which the dependent variable is the absolute decadal change in CO₂ intensity. The principal specification relates this change to percentage change in forest area, change in the hydropower share of electricity generation and absolute change in GDP per capita at purchasing power parity. These regressions are estimated on the full set of country–decade observations with non‑missing values for all included variables, and also separately for the 2000–2010 and 2010–2020 decades to examine whether associations differ across periods. Standard errors are computed using conventional formulas and with heteroskedasticity‑consistent corrections, and results are checked for sensitivity to the exclusion of individual countries where sample size permits.

To analyse changes in per‑capita LULUCF emissions we estimate models in which the dependent variable is the decadal change in LULUCF emissions per capita. The main specification relates this change to percentage change in forest area and change in the agriculture value added share of GDP. These regressions are estimated on the subset of countries for which LULUCF emissions and population data are available for both endpoints of at least one decade. Given the small sample size, we report conventional and heteroskedasticity‑consistent standard errors and examine the sensitivity of the estimates to clustering of standard errors by country and to re‑estimating the model while sequentially omitting each country from the sample.

The regression models are not intended to establish causal effects of forest change or the energy mix on emissions outcomes. Instead, they quantify conditional associations between decadal changes in key variables, conditional on the limited set of covariates available for all countries and decades in the sample. Interpretation of the estimated coefficients therefore focuses on direction and statistical significance rather than on structural parameters.

## Visualisation

To complement the numerical analysis we construct a set of article‑ready figures based on the level and delta panels. For each benchmark year we compute regional mean values of forest area, fossil CO₂ intensity of GDP and LULUCF emissions and present their evolution over time in a line chart. For the decadal analysis we produce scatterplots of percentage change in forest area against absolute change in fossil CO₂ intensity of GDP and against change in per‑capita LULUCF emissions. Points are labelled by country and decade, and countries are grouped into simple clusters to aid visual comparison. Specifically, Argentina, Brazil, Paraguay and Uruguay are grouped as an agricultural Southern Cone cluster, Bolivia, Colombia, Ecuador, Peru and Venezuela as an Andean and Amazon‑frontier cluster, and Chile, Guyana and Suriname as a residual group of other countries. In addition, we summarise changes in the electricity mix between 2000 and 2020 in a figure that displays the change in hydropower, coal, gas and non‑hydropower renewables shares for each country.

All figures are generated by Python scripts that read the analysis panels, apply consistent plotting styles and export high‑resolution images for use in the article. The figures are designed to illustrate the core empirical patterns documented in the Results section and to provide an intuitive complement to the regression analysis described above.

# Results

This section presents empirical results on the evolution of fossil CO₂ intensity of GDP, land‑use, land‑use change and forestry emissions, and the electricity mix in South America between 2000 and 2020. We first summarise descriptive patterns in levels and decadal changes. We then report regression results that relate changes in fossil CO₂ intensity and per‑capita LULUCF emissions to changes in forest area, the energy mix and economic structure. All findings are based on the analysis panels described in the Methods section.

## Descriptive patterns in levels and decadal changes

Fossil CO₂ emissions per unit of GDP at purchasing power parity declined in most South American countries over the study period. Between 2000 and 2020, the regional mean CO₂ intensity of GDP fell, with particularly pronounced reductions in countries that expanded hydropower and non‑hydropower renewables in their electricity mix. The decline in CO₂ intensity was not uniform: some countries exhibited large proportional reductions, while others showed relatively modest changes, but the overall pattern points to gradual decarbonisation of economic output.

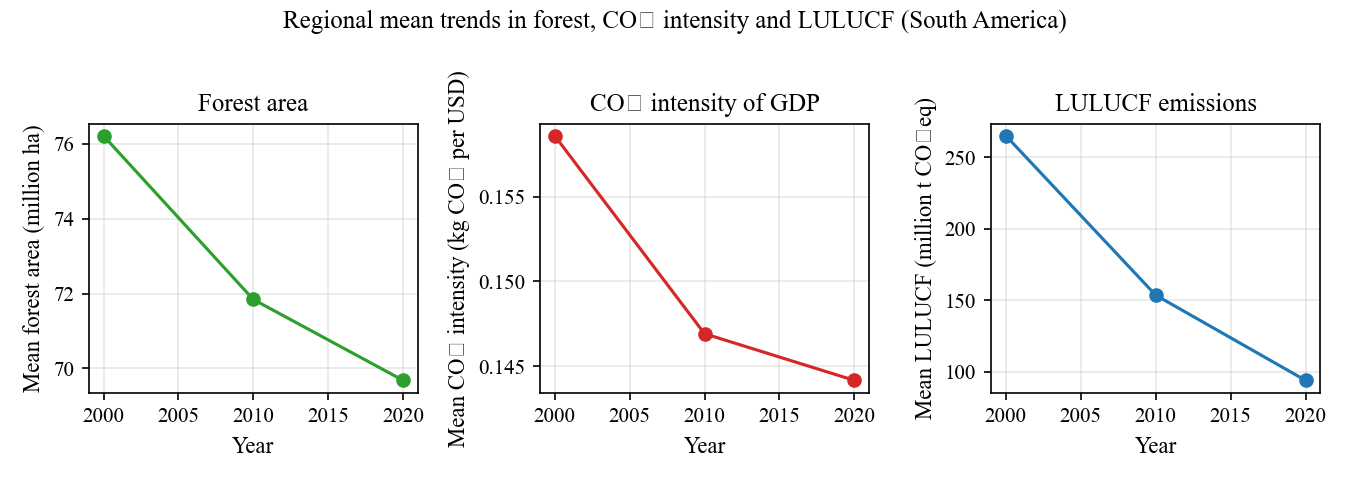
Forest area trajectories were heterogeneous across countries. Several countries in the region experienced net losses of forest area, especially those with large tropical forest frontiers and expanding agricultural frontiers. Others exhibited comparatively stable forest area or modest gains, reflecting different national land‑use policies and economic dynamics. When expressed as percentage changes over each decade, forest area declined in a substantial share of country–period observations, with larger relative losses in the early 2000–2010 decade than in the subsequent decade for some countries.

LULUCF emissions remained substantial throughout the period and exhibited marked variation across countries and over time. Countries with extensive deforestation or land‑use change in forested regions tended to have high absolute LULUCF emissions, while countries with smaller forest areas or more stable land use had lower totals. When expressed per capita, LULUCF emissions reveal sharp contrasts between countries with high rates of land‑use change and those with more limited land‑use dynamics. In several cases, per‑capita LULUCF emissions declined over time, while in others they remained elevated or increased, reflecting persistent or renewed land‑use pressures.

Economic and structural indicators show rising GDP per capita for most countries over 2000–2020, albeit from different starting levels. In several countries, the agriculture share of GDP declined, consistent with broader patterns of structural transformation towards industry and services. In others, agriculture retained a sizable share of economic output, often in tandem with expanding agricultural land. These differences in economic structure provide important context for interpreting the links between forest change, land‑use emissions and energy‑related decarbonisation.

The electricity mix evolved towards higher shares of hydropower and, in some cases, non‑hydropower renewables, although the extent and direction of change varied across countries. Some countries increased their reliance on hydropower from already high levels, while others expanded fossil‑fuel based generation from coal or natural gas. Access to electricity improved across the region, with increases in the share of the population connected to the grid. Taken together, these changes suggest that energy‑sector decarbonisation and energy access have progressed, but along distinct pathways across the twelve countries.

To highlight this heterogeneity we use a simple clustering of countries that is reflected in the decadal scatterplots. Argentina, Brazil, Paraguay and Uruguay form an agricultural Southern Cone group characterised by large agricultural sectors and substantial forest resources. Bolivia, Colombia, Ecuador, Peru and Venezuela form an Andean and Amazon‑frontier group with mixed hydrocarbon, extractive and agricultural activities. Chile, Guyana and Suriname constitute a small and diverse residual group. The clusters are used only for descriptive purposes and provide a convenient way to visualise how combinations of forest change, fossil CO₂ intensity and LULUCF emissions differ across regional development patterns.



**Figure 1. Regional trends in forest area, fossil CO₂ intensity of GDP and LULUCF emissions, 2000–2020**

**Table 2. Summary statistics for key variables by year (forest area, CO₂ intensity, LULUCF emissions, GDP per capita, agriculture share of GDP, hydropower share)**

| Variable | Year | Mean | Std. dev. | Min | Max |
| --- | --- | --- | --- | --- | --- |
| Forest area | 2000 | 76213,8 | 151272,4 | 1369 | 551088,6 |
| Forest area | 2010 | 71843,16 | 140246,1 | 1731,3 | 511580,7 |
| Forest area | 2020 | 69681,91 | 136165,9 | 2031 | 496619,6 |
| CO2 emissions per unit of GDP PPP (constant 2017 USD) | 2000 | 0,158583 | 0,068014 | 0,064 | 0,284 |
| CO2 emissions per unit of GDP PPP (constant 2017 USD) | 2010 | 0,146917 | 0,06251 | 0,066 | 0,266 |
| CO2 emissions per unit of GDP PPP (constant 2017 USD) | 2020 | 0,144167 | 0,06776 | 0,065 | 0,3 |
| Total LULUCF net GHG emissions | 2000 | 264845,7 | 753531,9 | -91141,8 | 2643654 |
| Total LULUCF net GHG emissions | 2010 | 153401,3 | 363111,8 | -97622,3 | 1276785 |
| Total LULUCF net GHG emissions | 2020 | 93821,85 | 188925 | 832,7144 | 687373 |
| GDP per capita, PPP (constant 2017 international dollars) | 2000 | 12783,62 | 5282,755 | 6146,029 | 22281,38 |
| GDP per capita, PPP (constant 2017 international dollars) | 2010 | 16939,45 | 6942,543 | 7571,678 | 28056,26 |
| GDP per capita, PPP (constant 2017 international dollars) | 2020 | 18133,72 | 5883,439 | 9000,976 | 27788,19 |
| Agriculture value added as share of GDP | 2000 |  |  |  |  |
| Agriculture value added as share of GDP | 2010 | 9,365 | 6,634025 | 3,62 | 28,53 |
| Agriculture value added as share of GDP | 2020 | 8,855455 | 3,783674 | 4,04 | 16,85 |
| Electricity production from hydroelectric sources, share of total | 2000 | 67,22813 | 28,3124 | 0,312883 | 100 |
| Electricity production from hydroelectric sources, share of total | 2010 | 55,26508 | 27,10947 | 0 | 99,99815 |
| Electricity production from hydroelectric sources, share of total | 2020 | 49,48468 | 28,85616 | 0,000832 | 99,99784 |

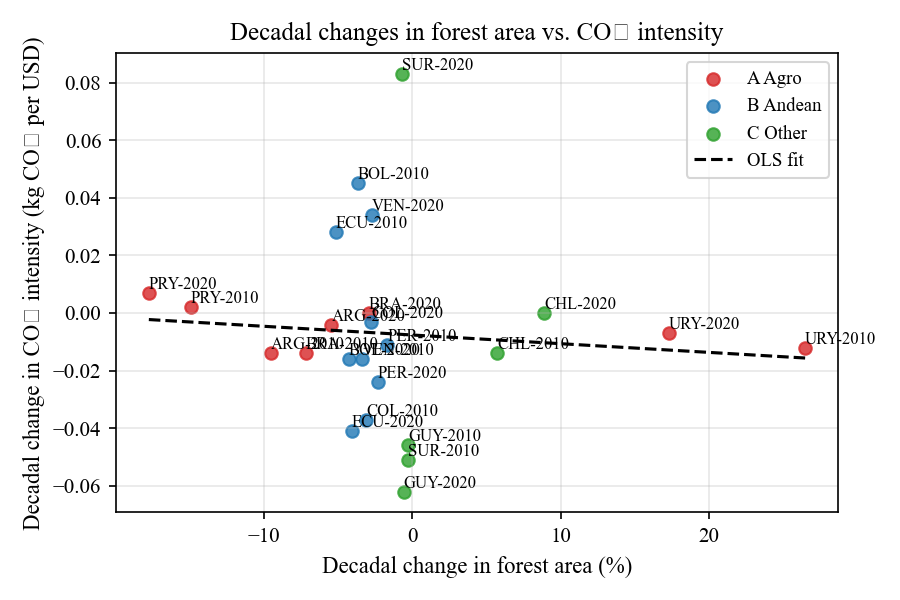
## Changes in fossil CO₂ intensity and the electricity mix

Decadal changes in fossil CO₂ intensity of GDP show that most country–decade observations experienced reductions in CO₂ intensity. The magnitude of these reductions differs substantially, with some countries exhibiting pronounced declines over both decades and others showing more modest progress or near‑stagnation in one of the decades. These patterns are consistent with gradual improvements in energy efficiency, shifts towards lower‑carbon energy sources and changes in the sectoral composition of output.

The decadal change in the hydropower share of electricity generation is positively associated with reductions in fossil CO₂ intensity of GDP. Country–periods in which the hydropower share increased tend to exhibit larger decreases in CO₂ intensity, while those with declining or stagnant hydropower shares show smaller improvements. In the regression model for decadal changes in fossil CO₂ intensity (Table 6, Model A), the coefficient on the change in hydropower share is negative and statistically significant (β ≈ −0.001, p ≈ 0.001 with heteroskedasticity‑consistent standard errors). Changes in GDP per capita also matter: higher income growth is associated with reductions in CO₂ intensity, with a small negative coefficient on the change in GDP per capita (β ≈ −5.6×10⁻⁶, p ≈ 0.02). These results are consistent with the idea that structural change and investment in cleaner technologies can accompany economic development.

Changes in forest area, as measured by the percentage change in forest area over each decade, do not exhibit a statistically significant association with changes in fossil CO₂ intensity of GDP in the decadal regressions. The estimated coefficient on percentage change in forest area is close to zero and not statistically significant at conventional levels (β ≈ −0.0005, p ≈ 0.38). Countries that experienced substantial forest loss did not systematically show larger decreases or increases in fossil CO₂ intensity than countries with stable or increasing forest area, once changes in hydropower share and GDP per capita are taken into account. This suggests that, over the time frame and spatial scale considered here, the main drivers of observed changes in CO₂ intensity of GDP are located within the energy system and broader economic structure rather than in forest area dynamics.

The clustered scatterplots illustrate how this pattern plays out in different regional settings. In the agricultural Southern Cone group, countries such as Brazil and Paraguay combine relatively low levels of fossil CO₂ intensity of GDP with sizeable forest losses over one or both decades. Paraguay, for example, maintained an almost entirely hydropower‑based electricity mix and correspondingly low fossil CO₂ intensity, yet its CO₂ intensity increased slightly between 2010 and 2020. In the Andean and Amazon‑frontier group, fossil CO₂ intensity levels are generally higher and energy mixes more diversified, while forest area changes range from moderate losses to more pronounced declines. The residual group of Chile, Guyana and Suriname spans a wide range of combinations of forest change and fossil CO₂ intensity. These examples underscore that improvements in fossil CO₂ intensity can coexist with continued forest loss and that the absence of a statistical association between forest change and CO₂ intensity reflects differences in sectoral and energy‑system structures rather than a lack of environmental relevance of forests.



**Figure 2. Decadal change in forest area versus change in fossil CO₂ intensity of GDP, by country and period**

**Table 3. Decadal changes in fossil CO₂ intensity of GDP, hydropower share and GDP per capita by country and period**

| Country | Period end year | Delta CO₂ intensity (kg CO₂ per USD) | Delta hydropower share (percentage points) | Delta GDP per capita (2017 international USD) |
| --- | --- | --- | --- | --- |
| ARG | 2010 | -0,014 | -6,87968 | 5774,876 |
| ARG | 2020 | -0,004 | -12,5416 | -4179,16 |
| BOL | 2010 | 0,045 | -17,4152 | 1425,649 |
| BOL | 2020 | -0,016 | -3,22878 | 1429,298 |
| BRA | 2010 | -0,014 | -9,04371 | 4056,811 |
| BRA | 2020 | 0 | -15,159 | -734,642 |
| CHL | 2010 | -0,014 | -10,2648 | 6591,498 |
| CHL | 2020 | 0 | -9,89361 | 2131,792 |
| COL | 2010 | -0,037 | -7,72772 | 3223,57 |
| COL | 2020 | -0,003 | -3,811 | 1824,436 |
| ECU | 2010 | 0,028 | -27,4562 | 2482,646 |
| ECU | 2020 | -0,041 | 33,6061 | 774,6285 |
| GUY | 2010 | -0,046 | -0,31288 | 2349,101 |
| GUY | 2020 | -0,062 | 0,000832 | 8859,735 |
| PER | 2010 | -0,011 | -25,3463 | 4389,923 |
| PER | 2020 | -0,024 | 1,937998 | 1550,582 |
| PRY | 2010 | 0,002 | -0,00185 | 2739,984 |
| PRY | 2020 | 0,007 | -0,00031 | 2253,084 |
| SUR | 2010 | -0,051 | -18,2103 | 6552,296 |
| SUR | 2020 | 0,083 | -22,2053 | -3681,11 |
| URY | 2010 | -0,012 | -14,6383 | 6127,777 |
| URY | 2020 | -0,007 | -48,167 | 2908,35 |
| VEN | 2010 | -0,016 | -6,25959 |  |
| VEN | 2020 | 0,034 | 10,09686 |  |

## Changes in LULUCF emissions per capita and forest dynamics

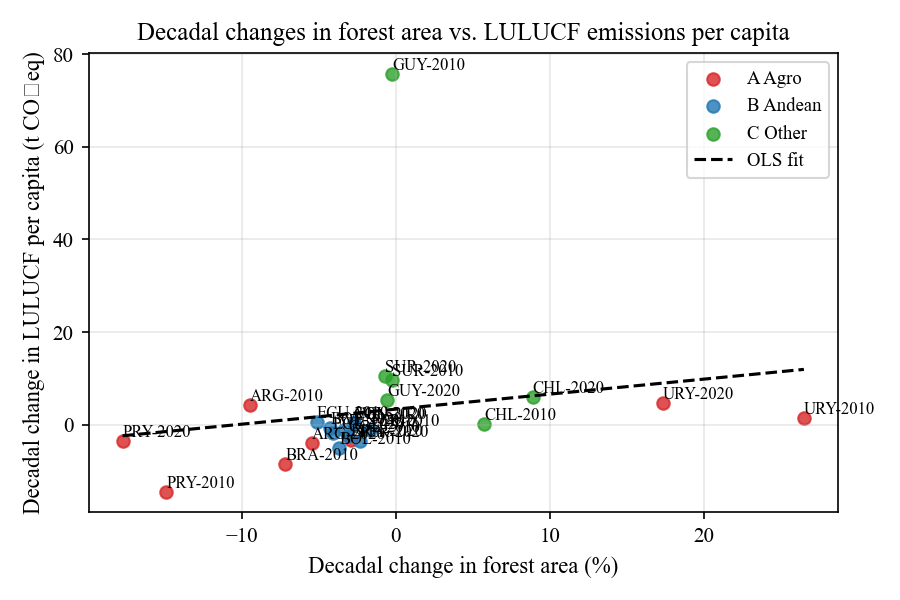
The decadal behaviour of per‑capita LULUCF emissions differs from the patterns observed for fossil CO₂ intensity. In the subset of countries and decades with complete data, changes in per‑capita LULUCF emissions are closely linked to changes in forest area. Country–periods with greater forest loss, as indicated by more negative percentage changes in forest area, tend to exhibit larger increases in per‑capita LULUCF emissions. Conversely, country–periods characterised by stable or modestly increasing forest area are more likely to show stable or declining per‑capita LULUCF emissions.

Regression models that relate decadal changes in per‑capita LULUCF emissions to percentage changes in forest area and changes in the agriculture value added share of GDP confirm this pattern. In the LULUCF model (Table 6, Model B), the estimated coefficient on percentage change in forest area is positive and statistically significant (β ≈ 0.33, p < 0.001), with the convention that more negative values correspond to larger forest losses. This indicates that greater forest loss is associated with higher increases in per‑capita LULUCF emissions. Changes in the agriculture value added share of GDP are negatively associated with changes in per‑capita LULUCF emissions: the coefficient on the change in the agriculture share is negative and significant (β ≈ −0.49, p ≈ 0.001), and country–periods in which the agriculture share of GDP declines tend to experience more favourable LULUCF emission outcomes in the sense of smaller increases or larger reductions in per‑capita LULUCF emissions. These associations persist when using cluster‑robust standard errors by country and when re‑estimating the models while leaving out one country at a time, within the limitations of the small sample size. Together, these findings suggest that both forest area dynamics and the economic role of agriculture are closely connected to the evolution of land‑use emissions per capita.

**Table 6. Regression results for decadal changes in fossil CO₂ intensity of GDP and per‑capita LULUCF emissions**

| Model | Dependent variable | Regressor | Coefficient | Std. error | p-value |
| --- | --- | --- | --- | --- | --- |
| Model A (Δ CO₂ intensity) | Δ CO₂ intensity (kg CO₂ per USD) | Constant | -0,0042 | 0,009086 | 0,643648 |
| Model A (Δ CO₂ intensity) | Δ CO₂ intensity (kg CO₂ per USD) | Delta forest area (%) | -0,00049 | 0,000568 | 0,383451 |
| Model A (Δ CO₂ intensity) | Δ CO₂ intensity (kg CO₂ per USD) | Delta hydropower share (percentage points) | -0,00099 | 0,000294 | 0,000741 |
| Model A (Δ CO₂ intensity) | Δ CO₂ intensity (kg CO₂ per USD) | Delta GDP per capita (2017 international USD) | -5,6E-06 | 2,34E-06 | 0,017354 |
| Model B (Δ LULUCF per capita) | Δ LULUCF per capita (t CO₂eq) | Constant | 0,919423 | 1,199201 | 0,443262 |
| Model B (Δ LULUCF per capita) | Δ LULUCF per capita (t CO₂eq) | Delta forest area (%) | 0,332988 | 0,080721 | 3,7E-05 |
| Model B (Δ LULUCF per capita) | Δ LULUCF per capita (t CO₂eq) | Delta agriculture share of GDP (percentage points) | -0,49478 | 0,147219 | 0,000777 |

The country clusters provide additional context for interpreting these associations. On average, the agricultural Southern Cone and the Andean and Amazon‑frontier groups both exhibit declines in forest area over the two decades, accompanied by moderate reductions in per‑capita LULUCF emissions, while the small residual group shows, on average, slight forest area gains and increases in per‑capita LULUCF emissions. Within each cluster, however, individual country–periods deviate from these averages, and the overall pattern remains that greater forest loss within a given structural context is associated with less favourable changes in per‑capita LULUCF emissions. The cluster perspective therefore complements the regression analysis by illustrating how similar mechanisms operate across different regional development profiles.



**Figure 3. Decadal change in forest area versus change in per‑capita LULUCF emissions, by country and period**

**Table 4. Decadal changes in per‑capita LULUCF emissions, forest area and agriculture share of GDP by country and period**

| Country | Period end year | Delta LULUCF per capita (t CO₂eq) | Delta forest area (%) | Delta agriculture share of GDP (percentage points) |
| --- | --- | --- | --- | --- |
| ARG | 2020 | -4,02429 | -5,43126 | -0,77 |
| BOL | 2020 | -0,71295 | -4,24264 | 3,61 |
| BRA | 2020 | -3,29728 | -2,92448 | 1,59 |
| CHL | 2020 | 5,954391 | 8,881416 | 0,42 |
| COL | 2020 | 0,334472 | -2,73958 | 1,15 |
| ECU | 2020 | -1,83682 | -4,07086 | 0,11 |
| GUY | 2020 | 5,367475 | -0,5641 | -11,68 |
| PER | 2020 | -3,47467 | -2,32199 | 0,87 |
| PRY | 2020 | -3,57645 | -17,7206 | -2,28 |
| SUR | 2020 | 10,61469 | -0,67693 | -1,98 |
| URY | 2020 | 4,681633 | 17,31069 | -0,63 |

## Changes in the electricity mix and energy‑system decarbonisation

To place the decadal results in the broader context of energy‑system change, we summarise shifts in the electricity mix between 2000 and 2020. Several countries increased the share of hydropower in electricity generation over the two decades, often starting from already high levels. In others, hydropower shares remained broadly stable, while coal‑ or gas‑based generation expanded. Non‑hydropower renewables, such as wind and solar, grew from near‑zero levels in 2000 to measurable shares in some countries by 2020, although their contribution to the regional electricity mix remained limited relative to hydropower and fossil fuels.

The countries that achieved the largest reductions in fossil CO₂ intensity of GDP over 2000–2020 generally combined rising hydropower shares, growing non‑hydropower renewables and increases in GDP per capita. Countries where fossil‑fuel based generation expanded without compensating increases in low‑carbon generation tended to experience smaller reductions in CO₂ intensity, even when GDP per capita grew. These patterns underscore the central role of the electricity mix in driving changes in fossil CO₂ intensity of output.



**Figure 4. Changes in electricity mix shares (hydropower, coal, gas, renewables excluding hydropower) between 2000 and 2020 by country**

**Table 5. Electricity mix shares by country in 2000 and 2020**

| Country | Year | Hydropower share (%) | Coal share (%) | Gas share (%) | Renewables excluding hydropower share (%) |
| --- | --- | --- | --- | --- | --- |
| ARG | 2000 | 40,5106 | 1,761917 | 47,02452 | -7,47881 |
| ARG | 2020 | 21,08927 | 1,299695 | 56,40286 | 6,173181 |
| BOL | 2000 | 50,12887 | 0 | 47,60309 | -0,36005 |
| BOL | 2020 | 29,48487 | 0 | 61,28483 | 6,424334 |
| BRA | 2000 | 87,24399 | 3,154395 | 1,165917 | 2,251767 |
| BRA | 2020 | 63,0413 | 2,789441 | 9,459829 | 20,13484 |
| CHL | 2000 | 46,19991 | 21,1263 | 26,07166 | 3,25116 |
| CHL | 2020 | 26,04146 | 31,0383 | 18,20628 | 22,74161 |
| COL | 2000 | 74,36415 | 5,103058 | 19,13473 | -0,22599 |
| COL | 2020 | 62,82543 | 11,81284 | 19,09389 | 2,451722 |
| ECU | 2000 | 71,72069 | 0 | 1,967678 | 0,002167 |
| ECU | 2020 | 77,87058 | 0 | 3,811444 | 1,84511 |
| GUY | 2000 | 0,312883 | 0 | 0 | 4,138443 |
| GUY | 2020 | 0,000832 | 0 | 0 | 7,225186 |
| PER | 2000 | 81,18911 | 1,742493 | 3,957015 | 0,699006 |
| PER | 2020 | 57,78085 | 0,267162 | 35,35631 | 6,194801 |
| PRY | 2000 | 100 | 0 | 0 | -0,01982 |
| PRY | 2020 | 99,99784 | 0 | 0 | 0,551712 |
| SUR | 2000 | 88,3959 | 0 | 0 | 16,22952 |
| SUR | 2020 | 47,9803 | 0 | 0 | -13,8685 |
| URY | 2000 | 92,92304 | 0 | 0 | 0,355034 |
| URY | 2020 | 30,11773 | 0 | 0 | 63,63091 |
| VEN | 2000 | 73,7484 | 0 | 16,98585 | 0 |
| VEN | 2020 | 77,58567 | 0 | 14,4671 | 0,128858 |

## Summary of key empirical findings

Across the twelve South American countries considered, fossil CO₂ emissions per unit of GDP at purchasing power parity declined between 2000 and 2020, with the magnitude of reductions varying across countries and decades. Regression models indicate that these reductions are significantly associated with increases in the hydropower share of electricity generation and with gains in GDP per capita, whereas percentage changes in forest area do not exhibit a statistically significant association with decadal changes in fossil CO₂ intensity of GDP once energy and income dynamics are taken into account.

In contrast, land‑use, land‑use change and forestry emissions per capita are closely linked to forest area dynamics and the economic role of agriculture. Countries and decades with larger relative forest losses tend to show greater increases in per‑capita LULUCF emissions, while declines in the agriculture share of GDP are associated with more favourable LULUCF emission trajectories. These patterns are consistent across ordinary least squares estimates with heteroskedasticity‑consistent and cluster‑robust standard errors and remain qualitatively similar in leave‑one‑country‑out analyses, subject to the constraints imposed by the small sample.

Taken together, the results show that energy‑sector decarbonisation and land‑use emissions follow distinct trajectories in South America. It appears feasible to reduce fossil CO₂ intensity of GDP through changes in the electricity mix and structural economic change, even in the presence of continued forest loss. At the same time, forest loss remains tightly linked to per‑capita LULUCF emissions, indicating that improvements in energy‑related emissions do not automatically translate into improvements in land‑use emissions. These empirical findings motivate the Discussion and Conclusion sections, where we interpret the results in light of the Sustainable Development Goals and the broader literature on decarbonisation and land‑use change.

# Discussion

This study examined how changes in forest area, land‑use, land‑use change and forestry emissions and the electricity mix relate to the fossil CO₂ intensity of GDP in twelve South American countries over the period 2000–2020. The empirical results point to two central patterns. First, fossil CO₂ emissions per unit of economic output declined in most countries, and these reductions are statistically associated with changes in the electricity mix and income growth rather than with changes in forest area. Second, per‑capita LULUCF emissions remain closely linked to forest area dynamics and the economic role of agriculture. In this section, we interpret these findings in light of the existing literature, discuss their implications for the Sustainable Development Goals and highlight limitations and priorities for future research.

The cluster perspective introduced in the Results section helps to situate these patterns in the region’s heterogeneous development pathways. The agricultural Southern Cone group illustrates that low fossil CO₂ intensity of GDP, supported by hydropower and non‑hydropower renewables, can coexist with substantial forest loss and associated land‑use emissions. The Andean and Amazon‑frontier group combines more diversified energy mixes, higher average fossil CO₂ intensity and continued forest dynamics at the extractive and agricultural frontiers. The small residual group of Chile, Guyana and Suriname exhibits intermediate or mixed profiles. These groupings are heuristic and descriptive, but they underscore that similar statistical relationships between decadal changes in the electricity mix, forest area and emissions can have different policy implications depending on the structural context.

The decadal regressions indicate that increases in the hydropower share of electricity generation and rise in GDP per capita at purchasing power parity are associated with reductions in fossil CO₂ intensity of GDP, while decadal percentage changes in forest area are not significantly associated with changes in CO₂ intensity once energy and income dynamics are controlled for. This pattern is consistent with country‑specific scenario and policy analyses that emphasise the centrality of the energy system for mitigation in South America. Studies of Brazil’s mitigation pathways in a well‑below‑2 °C world and the relative role of disruptive technologies versus land‑based mitigation point to a comparatively low‑emission electricity system and stress that further emission reductions in Brazil depend on both technological change and land‑use policies in a broader decarbonisation strategy (Köberle et al., 2020). Work on the potential of a bioeconomy to reduce Brazilian emissions towards 2030 underlines that changes in the energy mix, energy efficiency and structural economic change are important determinants of future emission trajectories (Machado et al., 2020). At the same time, country‑level analyses for Chile and Colombia emphasise the influence of renewable energy deployment, technological innovation and integration into global markets on emission reduction prospects (Raihan, 2023). Against this background, our finding that decadal reductions in fossil CO₂ intensity are associated with changes in the electricity mix and income growth aligns with the view that energy‑system decarbonisation is a primary channel through which South American countries reduce fossil CO₂ emissions per unit of output.

At the same time, the absence of a statistically significant association between decadal percentage changes in forest area and changes in fossil CO₂ intensity of GDP does not imply that forest dynamics are irrelevant for national mitigation strategies. Instead, it reflects the fact that fossil CO₂ intensity of GDP is largely determined by fossil‑fuel use in energy and industry, while forest change affects a different component of the greenhouse gas balance. The literature on agriculture‑driven deforestation and associated emissions in the tropics shows that land‑use change contributes substantially to total emissions but primarily through the LULUCF component rather than through energy‑related CO₂ (Carter et al., 2018). Work on global and pantropical AFOLU emissions and removals similarly documents the large contribution of land‑use emissions to national and regional greenhouse gas budgets, particularly in forest‑rich tropical countries (Nyawira et al., 2024; Houghton & Castanho, 2023). Our results fit into this picture by showing that, for the twelve South American countries considered here, energy‑related CO₂ intensity of GDP can improve even as forest area declines, while LULUCF emissions per capita remain directly connected to forest area dynamics.

Country‑specific examples from the agricultural Southern Cone group illustrate the limitations of focusing solely on fossil CO₂ intensity. Paraguay maintains an almost entirely hydropower‑based electricity mix and correspondingly low fossil CO₂ intensity of GDP, yet its fossil CO₂ intensity increased slightly between 2010 and 2020 and the country experienced sizeable forest losses over both decades. Brazil records substantial reductions in fossil CO₂ intensity between 2000 and 2010 and stable intensity thereafter, alongside a decline in the hydropower share of electricity generation and continued, though slowing, forest loss. Uruguay and Chile, in turn, combine increases in reported forest area with rapid growth in non‑hydropower renewable electricity. Taken together, these cases show that favourable trends in fossil CO₂ intensity can coincide with continued forest loss or with forest gains that reflect complex mixes of natural and managed forests, and they highlight the importance of treating energy‑related and land‑use emissions as complementary rather than interchangeable dimensions of climate performance.

The close association between decadal changes in per‑capita LULUCF emissions, forest area and the agriculture share of GDP that we observe in the data is consistent with a large body of work on the drivers of deforestation and land‑use emissions in Brazil and other Latin American countries. Studies that examine the role of land‑use emissions in achieving Brazil’s nationally determined contribution highlight that continued reductions in land‑use and agricultural emissions are essential for meeting national mitigation targets and that policy choices on deforestation control and agricultural expansion have long‑lasting implications for the LULUCF trajectory (Wiltshire et al., 2022). Analyses of reductions in land‑use change and agricultural emissions in Brazil in the context of the country’s commitments under the Paris Agreement document that policy interventions and enforcement can substantially alter deforestation trends and associated emissions (Ferreira‑Filho & Horridge, 2016). Scenario‑based assessments of Brazil’s Forest Code indicate that legal and institutional frameworks governing land use can affect both environmental outcomes and agricultural production over coming decades (Soterroni et al., 2018). Our finding that decadal LULUCF emission changes are closely associated with forest area dynamics and changes in the agriculture share of GDP is consistent with these studies and emphasises that the structure of the economy and land‑use policy continue to shape the land‑use emissions pathway.

Recent work on agricultural production, livestock and GHG emissions in the Brazilian Amazon and broader Latin America further supports the connection between agricultural expansion, cattle production, land‑use change and emissions (Rodrigues et al., 2023; Sandoval & Burkart, 2023). Studies of global economic and diet transitions and their effects on Latin American and Caribbean forest change highlight the role of changing consumption patterns and external demand for agricultural commodities in driving forest loss (López‑Carr et al., 2022). Evidence on greenhouse gas emissions from land‑use change in Brazil between 1990 and 2015 shows that land‑use change remains a major contributor to national emissions despite progress in other sectors (Sanquetta et al., 2020). Together with these contributions, our results reinforce the view that forest loss and agricultural expansion are tightly linked to LULUCF emissions, and that improvements in energy‑sector emissions do not automatically resolve the land‑use component of national greenhouse gas inventories.

The relationship between land‑use policies, deforestation control and broader development objectives has direct implications for the Sustainable Development Goals. Our findings speak most directly to SDG 7 on affordable and clean energy, SDG 13 on climate action and SDG 15 on life on land, but they are also connected to SDG 2 on zero hunger and SDG 16 on peace, justice and strong institutions. The observed decline in fossil CO₂ intensity of GDP, associated with changes in the electricity mix and progress in access to electricity, is broadly aligned with SDG 7 and SDG 13, which call for expanded access to modern energy services and substantial reductions in greenhouse gas emissions. However, the persistence of forest loss and its tight link to per‑capita LULUCF emissions indicates that SDG 15, which aims to halt deforestation and reverse land degradation, remains under pressure in several countries. The association between changes in the agriculture share of GDP and LULUCF emissions illustrates the tensions and potential synergies between SDG 2 and SDG 13: increasing agricultural production to improve food security and export revenues can come at the cost of higher land‑use emissions if it is achieved through area expansion rather than intensification and improved practices.

Our use of governance and social indicators from CEPALSTAT, including measures of control of corruption, rule of law, income inequality and rural extreme poverty, underscores the relevance of SDG 16. Although the small sample and limited temporal coverage prevent formal estimation of governance effects in our decadal regression models, the descriptive variation in these indicators across countries points to substantial differences in institutional capacity and social outcomes. Studies that examine wood production and its correlation with socioeconomic and environmental indicators in the Amazon region, as well as research on regional development and greenhouse gas emissions in Amazonian states, highlight that institutional quality and enforcement play a central role in mediating the relationship between economic development, land‑use change and emissions (Silva et al., 2023; Imori et al., 2016). Work on hotspots of land‑use emissions and comparisons of land‑use emission datasets further points to the importance of consistent and transparent monitoring for effective governance (Roman‑Cuesta et al., 2016). In this broader context, our descriptive use of governance indicators suggests that meeting SDG 13 and SDG 15 in South America will depend not only on technical mitigation options in energy and land use, but also on institutional strength and social conditions.

The distinction between fossil CO₂ intensity of GDP and land‑use emissions per capita that emerges from our results is also important for how climate performance is assessed. Emission accounting and driver analyses for South American countries emphasise that both energy‑related emissions and LULUCF emissions contribute to national greenhouse gas profiles (Peng et al., 2024). Pantropical assessments of AFOLU emissions and removals and LULUCF datasets based on national greenhouse gas inventories show that land‑use emissions account for a large share of net emissions in many tropical countries and that their temporal dynamics differ from those of energy‑related emissions (Nyawira et al., 2024; LULUCF data based on national inventories, 2022). If climate performance is evaluated solely through indicators such as CO₂ emissions per unit of GDP, countries that have reduced fossil CO₂ intensity while continuing to lose forest area may appear to perform better than their total emissions trajectories warrant. Our results provide a concrete illustration of this concern for South America, where energy‑sector decarbonisation and land‑use emissions follow different trajectories.

The heterogeneity of energy‑system pathways in the region also has implications for resilience to climate impacts and for hydropower‑dependent systems. Studies of the 2015–2016 megadrought in Colombia and its implications for energy transitions emphasise the interactions between climate variability, hydropower reliance and energy‑system change (Weng et al., 2020). The literature on trade‑offs and synergies between climate change mitigation, biodiversity preservation and agro‑economic development in Brazil and on land conservation under a renewable energy transition suggests that mitigation strategies need to account for cross‑sectoral linkages between water, energy, land and biodiversity (Gérard et al., 2025; Borba et al., 2024). Our finding that hydropower expansion is associated with reductions in fossil CO₂ intensity highlights the benefits of low‑carbon electricity for SDG 7 and SDG 13, but attention to hydrological risks and ecosystem impacts remains important to avoid unintended consequences for SDG 6 on water and SDG 15 on terrestrial ecosystems.

This study has several limitations that should be taken into account when interpreting the results. First, the empirical analysis is based on twelve countries and three benchmark years, which implies that the number of country–decade observations in the delta panel is small. This restricts the complexity of regression specifications that can be estimated without over‑fitting and limits the precision of coefficient estimates. Second, the analysis relies on nationally aggregated data from international statistical agencies. While these data provide a consistent basis for cross‑country comparison, they cannot capture subnational heterogeneity in land‑use change, energy systems or governance, which is known to be important in large and diverse countries such as Brazil, Colombia or Peru. Third, the decadal‑difference specification controls for time‑invariant country characteristics and focuses on medium‑term changes, but it cannot identify causal effects of forest change, hydropower expansion or income growth on emissions outcomes. The estimated coefficients should therefore be interpreted as conditional associations rather than structural parameters.

Fourth, the variable set is constrained by the coverage of the underlying data sources. Several potentially relevant indicators, such as detailed innovation metrics, commodity‑specific trade data or measures of enforcement intensity, are not available with sufficient coverage across countries and time to be included in the decadal models. Even within the available data, some series related to methane or total CO₂ emissions are not consistently reported in the current versions of the World Bank or FAOSTAT databases, which is why they are excluded from our analysis panels. Finally, the regression models do not explicitly incorporate price dynamics, international demand or policy shocks, which play a central role in many country‑specific studies of deforestation and energy transitions. As a result, the models cannot account for all relevant drivers of emission changes and should be seen as a complementary, region‑wide perspective rather than as a replacement for detailed national case studies.

These limitations suggest several directions for future research. One avenue is to extend the analysis with more frequent temporal data as additional years become available and to explore panel‑data models that combine decadal and annual information. Another is to integrate subnational land‑use change datasets with national energy and macroeconomic indicators to better capture within‑country heterogeneity, building on work that compares bottom‑up estimates of land‑use emissions with top‑down atmospheric measurements in the Amazon and other tropical regions (Tejada et al., 2023). A third direction is to link the aggregate indicators used here to more detailed analyses of policies, enforcement and governance, drawing on national greenhouse gas inventories and case studies of specific biomes or commodity frontiers. Such work would enable a more explicit treatment of SDG 16 and of the institutional dimensions of land‑use and energy transitions.

Within these constraints, the present study contributes a region‑wide, empirically grounded perspective on how energy‑sector decarbonisation and land‑use emissions evolve in South America and how they relate to forest area and economic structure. The evidence that fossil CO₂ intensity of GDP can decline through changes in the electricity mix and structural change, while LULUCF emissions per capita remain closely tied to forest loss and agriculture, underscores the need for integrated mitigation strategies that simultaneously address SDG 7, SDG 13 and SDG 15. It also highlights the importance of considering land‑use emissions explicitly when assessing climate performance and designing policies that aim to reconcile climate mitigation, biodiversity conservation and agricultural development in the region. These themes are taken up in more detail in the Conclusion section, where we synthesise the implications of the empirical findings and outline policy‑relevant messages for decision‑makers in South America and beyond.

# Conclusion

This study analysed how changes in forest area, land‑use, land‑use change and forestry emissions and the electricity mix relate to the fossil CO₂ intensity of GDP in twelve South American countries between 2000 and 2020. By constructing harmonised country–year and decadal‑change panels from CEPALSTAT, World Development Indicators and FAOSTAT, and by estimating simple linear regressions on decadal differences, we documented how energy‑related and land‑use emissions have evolved along partly separate trajectories. The analysis shows that reductions in fossil CO₂ intensity of GDP are closely associated with changes in the electricity mix and income growth, while per‑capita LULUCF emissions remain tightly linked to forest area dynamics and the economic role of agriculture. Taken together, these findings highlight the need to consider both energy‑sector decarbonisation and land‑use emissions when assessing climate performance and designing mitigation strategies in South America.

For fossil CO₂ emissions, most countries experienced declines in emissions per unit of GDP at purchasing power parity over the two decades. The decadal regressions indicate that these reductions are significantly associated with increases in the hydropower share of electricity generation and with gains in GDP per capita, whereas percentage changes in forest area do not exhibit a statistically significant association with changes in fossil CO₂ intensity once energy and income dynamics are controlled for. This pattern is consistent with national and regional studies that emphasise the central role of low‑carbon electricity and structural economic change in decarbonising energy systems in South America. It suggests that, within the time frame and spatial scale considered here, energy‑system transitions and broader development processes, rather than forest dynamics, are the main drivers of changes in fossil CO₂ intensity of GDP.

At the same time, the analysis of land‑use, land‑use change and forestry emissions paints a different picture. When LULUCF emissions are expressed in per‑capita terms and examined in decadal changes, they are closely associated with forest area dynamics and with the agriculture value added share of GDP. Country–periods with greater forest loss tend to experience larger increases in per‑capita LULUCF emissions, while declines in the agriculture share of GDP are associated with more favourable LULUCF trajectories. These relationships are stable across ordinary least squares estimates with heteroskedasticity‑consistent and cluster‑robust standard errors and remain qualitatively similar in leave‑one‑country‑out sensitivity tests, within the constraints imposed by the small sample size. The results therefore reinforce the view that forest conservation and the structure of agricultural production remain central to land‑use emissions in South America.

The country clusters introduced in the Results section help to situate these findings in the region’s heterogeneous development pathways. Countries in the agricultural Southern Cone group, such as Brazil and Paraguay, often combine low or declining fossil CO₂ intensity of GDP with substantial forest losses over one or both decades. Countries in the Andean and Amazon‑frontier group, including Bolivia, Colombia, Ecuador, Peru and Venezuela, display more diversified energy mixes and higher average fossil CO₂ intensity, alongside continued forest dynamics at extractive and agricultural frontiers. The small residual group of Chile, Guyana and Suriname exhibits mixed profiles with varying combinations of forest change, energy mixes and emissions. Across these contexts, the empirical message is consistent: improvements in fossil CO₂ intensity of GDP can coexist with continued forest loss, and favourable trends in energy‑related emissions do not automatically translate into favourable trends in land‑use emissions.

These findings have direct implications for how climate performance is monitored and for the interpretation of commonly used indicators. Measures such as fossil CO₂ emissions per unit of GDP are useful for tracking progress in energy‑sector decarbonisation, but they capture only part of the greenhouse gas balance in forest‑rich economies. In South America, where electricity generation is often relatively low in fossil carbon and land‑use emissions can be large, relying solely on fossil CO₂ intensity risks overstating progress towards climate mitigation. Our results provide an empirical illustration of this concern by showing that countries can reduce fossil CO₂ intensity of GDP through changes in the electricity mix and economic structure while LULUCF emissions per capita remain closely tied to forest loss and agricultural expansion. For policy analysis and international reporting, this underscores the importance of integrating land‑use emissions explicitly into assessments of climate performance.

The study also speaks to the interplay between climate mitigation and the Sustainable Development Goals. The observed decline in fossil CO₂ intensity of GDP, driven by changes in the electricity mix and improvements in energy access, aligns with SDG 7 on affordable and clean energy and SDG 13 on climate action. However, the persistence of forest loss and its tight link to per‑capita LULUCF emissions indicates that SDG 15, which calls for halting deforestation and reversing land degradation, remains under pressure in several countries. The association between changes in the agriculture share of GDP and LULUCF emissions highlights the tensions and potential synergies between SDG 2 on zero hunger and SDG 13: expanding agricultural output to improve food security and export revenues can either intensify land‑use emissions if achieved through area expansion, or contribute to mitigation if combined with intensification and improved practices. Finally, the descriptive variation in governance and social indicators across countries, and the supporting literature on institutional quality and emissions, underscore the relevance of SDG 16 on peace, justice and strong institutions for both energy‑sector and land‑use mitigation.

Several limitations should be kept in mind when interpreting these conclusions. The analysis is based on twelve countries and three benchmark years, which constrains the number of country–decade observations and limits the complexity of regression specifications. The models rely on nationally aggregated data from international statistical agencies and do not capture subnational heterogeneity in land‑use change, energy systems or governance. The decadal‑difference design helps to focus on medium‑term changes and to abstract from time‑invariant country characteristics, but it cannot identify causal effects of forest change, hydropower expansion or income growth on emissions outcomes. In addition, the variable set is restricted by the coverage of the underlying data sources; several potentially relevant indicators, such as enforcement intensity or commodity‑specific trade flows, are not consistently available for all countries and decades and are therefore not included in the analysis panels.

These constraints point to priorities for future research. Extending the analysis to include additional years as data become available would allow for more flexible panel‑data models and a richer characterization of temporal dynamics. Linking the national‑level indicators used here to subnational land‑use change datasets could help to uncover within‑country heterogeneity in the relationships between forest change, energy systems and emissions. Combining the aggregate perspective with more detailed studies of policies, enforcement and governance could shed further light on the institutional conditions under which energy‑sector decarbonisation and reductions in land‑use emissions can proceed in tandem. Finally, continued efforts to harmonise and integrate energy, land‑use and emissions data will be essential for monitoring progress towards SDG 7, SDG 13 and SDG 15 in South America.

Within these limitations, the present study contributes a region‑wide, empirically grounded perspective on the forest–energy–emissions nexus in South America. It shows that energy‑sector decarbonisation and land‑use emissions have followed distinct, though interconnected, trajectories over the past two decades, and it highlights the importance of considering both dimensions when evaluating climate performance and designing mitigation strategies. For policy makers and stakeholders in the region, the results suggest that sustained progress towards climate and development goals will require simultaneous attention to clean energy transitions, forest conservation and the structure of agricultural and land‑using sectors, supported by strong institutions and transparent data.

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