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Changing Climate in Brazil

Key Vulnerabilities and Opportunities

Chen Chen, Koralai Kirabaeva, Christina Kolerus, Ian Parry, and Nate Vernon

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Changing Climate in Brazil: Key Vulnerabilities and Opportunities

Prepared by Chen Chen, Koralai Kirabaeva, Christina Kolerus, Ian Parry, and Nate Vernon*

Authorized for distribution by Ana Corbacho and James Roaf
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ABSTRACT: This paper assesses the Brazilian economy's exposure to climate change focusing on two key areas: agriculture and hydropower. While climate vulnerabilities are significant and recent patterns of land-use further amplify climate change risk, Brazil's opportunities for green growth are vast. Given geography and existing infrastructure, notably the very green energy mix, Brazil can boost its economic potential while mitigating a potential tradeoff between energy use, emissions, and growth. Policy options to address key vulnerabilities and leverage opportunities include boosting the Amazon's resilience via fiscal incentives for forest protection, investing in climate smart agriculture and insurance guided by sustainable feebates, continuing the diversification of renewable power generation, and stimulating green growth while greening the financial sector.

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Author's E-Mail Address:	cchen3@imf.org, kkirabaeva@imf.org, ckolerus@imf.org, iparry@imf.org, nvernon@imf.org

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WORKING PAPERS

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Introduction

Changing climate conditions are already affecting Brazil's economy. Rising temperatures in Brazil (between +1°C and +2.2°C by 2050) and temperature variability have increased both present occurrences and the future likelihood of extreme weather events. The most common extreme events in Brazil are floods, which have more than doubled relative to the 1980s-90s[1] and often result in physical and human capital losses, particularly if linked to landslides. They mostly occur in the form of flash floods or riverine floods and can cause temporary productivity losses and disruptions in infrastructure,[2] significant fiscal costs, and sometimes durable output scarring. Second most frequent, yet costliest climate hazards are droughts, which impact agricultural output and electricity prices (BCB, 2023a), and extreme heat waves, which mainly occur in urban areas. The World Bank estimates that extreme weather events have generated yearly output losses of 0.13 percent of GDP on average over the past 20 years (World Bank CCDR, 2023).

Agriculture and power generation are key sectors at risk, with potential repercussions for the financial sector. In addition, patterns of land-use amplify climate change risks by profoundly affecting water cycles. Increasing dry-season length and drought frequency[3] have diminished the Amazon's resilience against shocks and may have already pushed the Amazon close to a critical threshold of rainforest dieback (Boulton et al 2022).[4] Deforestation has further increased the likelihood of reaching a tipping point that would durably disrupt water cycles, accelerate erosion, limit carbon storage, and release sizeable amounts of carbon into the atmosphere. In decreasing the availability of fresh water, deforestation makes water-intensive sectors more vulnerable (such as agriculture and hydropower, but also mining and industry). While estimates of the impact of climate change on the economy are subject to significant uncertainties, some estimates quantify the output loss of reaching the Amazon tipping point for Brazil alone at 10 percent of 2022 GDP through 2050 (Zili et al, 2020).

Brazil is in a unique position to green its economy and boost potential growth. Building on Brazil's very green energy mix and world-wide leading biodiversity, Brazil can increase its economic potential while mitigating a potential tradeoff between energy use, emissions, and growth. Opportunities for the private sector include the export of green energy as well as export-oriented manufacturing to seize growing demand for green goods and services. The sizable pipeline of renewable energy projects will help further diversify the renewables energy portfolio and prepare for the potential export of green energy, but needs to be accompanied by investments in the grid and in storage facilities. The recent approval of a cap-and-trade carbon market to complement the voluntary carbon market can further help green Brazil's economy from a regulatory perspective. At the same time, adaptation investments in climate-smart agriculture and forest protection as well as well-designed fiscal

1 EM-DAT, CRED / UCLouvain, 2023, Brussels, Belgium

2 More than 5 percent of Brazil's road and railway infrastructure is exposed to flood risks (World Bank CCDR, 2023).

3 The current 2023-24 exceptional drought in the Amazon basin left water levels at record low.

4 Evidence on reaching the Amazon tipping point, however, is mixed and some studies suggest that the decreasing trend in forest resilience is limited, and has been partly reversed in recent years (Tao et al, 2022).

incentives for forestry and agriculture are needed to foster resilience of Brazil's ecosystems and lower emissions towards meeting Brazil's goal of net zero emissions in 2050.

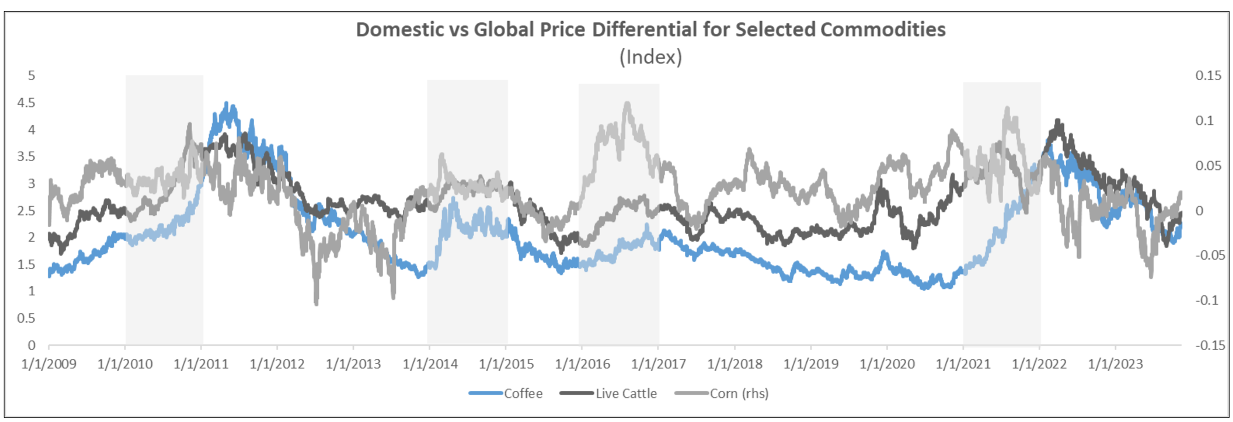
The paper discusses key vulnerabilities in section II, and then lays out macro policy options in section III building on cross-country experience. In particular, the Paper covers policies to (i) boost the Amazon's resilience; (ii) invest in climate-smart agriculture and insurance; (iii) diversify energy sources; and (iv) leverage opportunities for green growth.

Key Vulnerabilities

Agriculture

Traditional agriculture production in Brazil, i.e. farming and livestock, contributes only around 7 percent of GDP to Brazil's economy. Agribusiness – traditional agriculture plus processing and agro-related services – amount to almost 25 percent of GDP and about 50 percent of total exports. Adverse weather conditions, including through stronger episodes of El Niño, which alter precipitation patterns, as well as increased drought risks have a profound impact on agricultural production and prices, and thus on Brazil's economy. The 2010 drought, for instance, widened the price differential between domestic and international markets by 50 percent for coffee and live cattle, and 100 percent for corn, measured year-on-year as of end 2011 (Figure 1), corresponding to a domestic price increase of around 50 percent for each product (and almost doubling prices for coffee and corn throughout February 2011). Domestic prices for soybeans and sugar increased by 25 percent year on year. Similar magnitudes were observed during subsequent droughts, with some variability across products.[5]

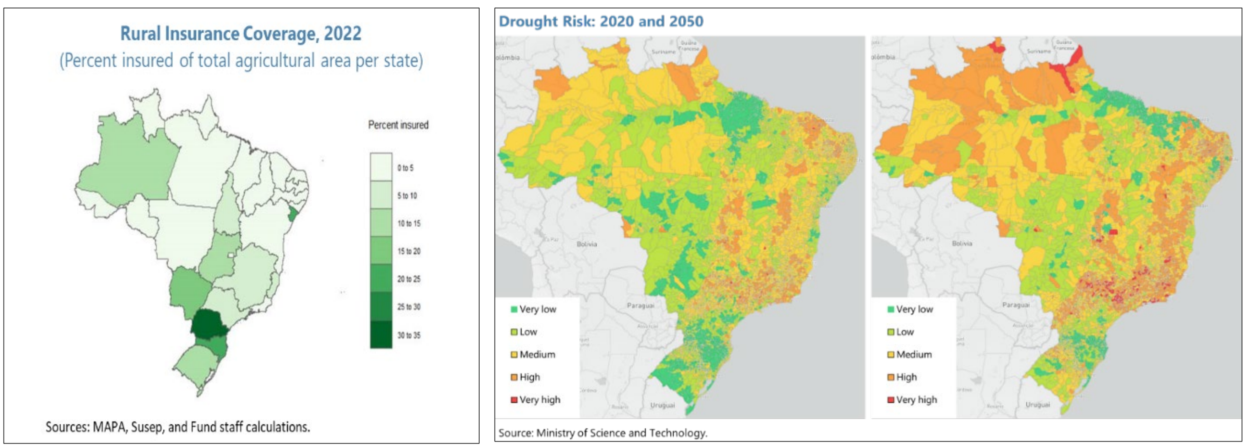
Figure 1. Commodity Price Differentials and Past Droughts



5 The timing of droughts differs across sources, with varying intensity across regions. Overall, historical droughts took place in 1997-98, 2002-03, 2010 and 2012-2018 (GAR 2021), with some sources singling out 2014 and 2016. Municipalities affected by drought included 1061 in 2012, 551 in 2013, 229 in 2014, 621 in 2015, 462 in 2016, and 617 in 2017 (Cunha et al. 2019).

Increasing frequency and length of dry seasons raises drought risks for agricultural production in both the Northern and Southern regions of Brazil.[6] The impact, however, is more severe in the Northeast as the region's small-scale agriculture is rainfed, with limited irrigation systems in place, and significantly lower insurance coverage. Only about 20 percent of farming activity is covered by insurance on average,[7] with Southern farmers significantly more insured than their peers in the North and Northeast. However, drought risks affect both Northern and Southern regions (Figure 2). Droughts have further diminished the Amazon and Cerrado biomes' resilience against shocks, and, aided by deforestation, increased the likelihood of reaching a tipping point that would durably disrupt water cycles. The World Bank quantifies the output loss of reaching the Amazon tipping point for Brazil alone at 10 percent of 2022 GDP through 2050 (World Bank CCDR, 2023).

Figure 2. Rural Insurance and Drought Risk



Hydropower generation

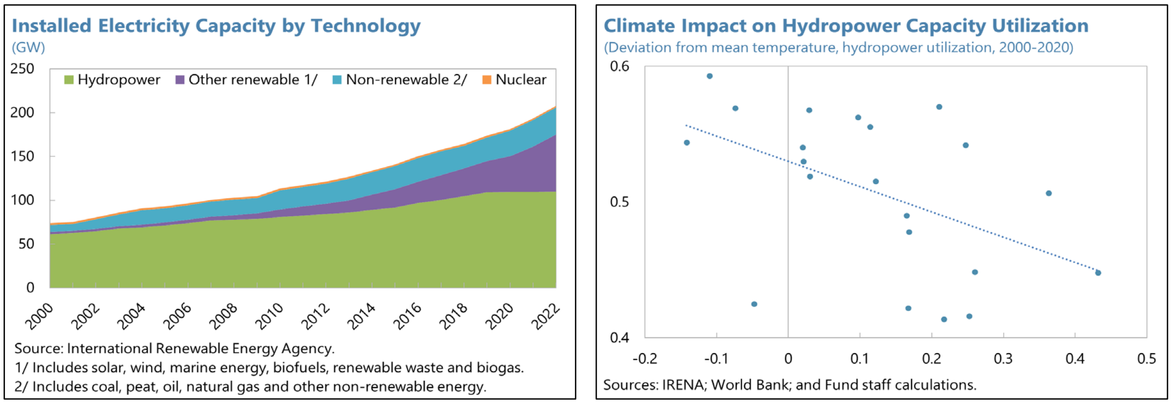
Brazil's energy mix is one of the greenest worldwide, with almost 90 percent of electricity generated by renewables in 2022. Hydropower is the largest energy source, producing around 60 percent of Brazil's electricity, down from 90 percent during the 2000s as other renewables were steadily expanding (Figure 3, left). Changing climate conditions, including lower water availability and shifting rainfall patterns, will affect hydropower generation, leading to higher volatility and reduced output. At the same time, power demand is increasing due to economic growth as well as increased demand for cooling. We estimate that past deviations from mean temperatures by +0.1C in a calendar year have led to a lower capacity utilization of 2-3 percent in the same year, implying significant volatility already at current climate conditions (Figure 3, right). A drop in hydropower generation pushes up energy costs as (more costly) thermal power plants need to be switched on

6 Agriculture is estimated to lose 1 percent of its sectoral GDP per year due to extreme weather events (World Bank CCDR, 2023).

7 Source: Superintendência de Seguros Privados (SUSEP), Brazil's supervisory body for private insurers.

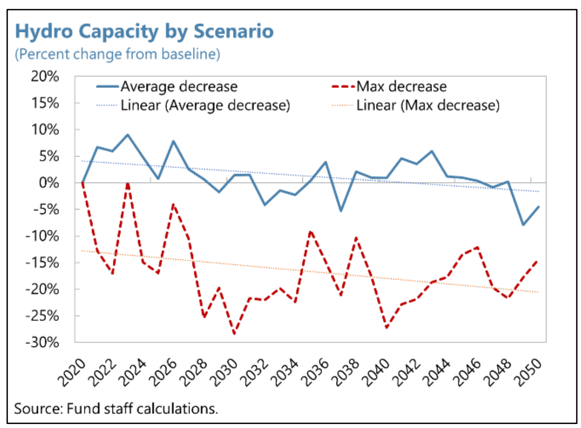
to fill the gap. The 2021 drought, for instance, increased inflation by 0.7 percentage points (BCB 2022a) mainly through increasing electricity prices.

Figure 3. Electricity Mix and Climate Impact on Hydropower



In the coming years, slow-moving temperature increases and precipitation changes are expected to further intensify disruptions to hydropower supply, lower dispatchable hydro capacities,[8] and increase the potential for power gaps:

- **Climate impact on hydropower generation.** Projections for dispatchable hydro capacity in Brazil are taken from the Pacific Northwest National Laboratory (PNNL)'s global hydrological model, Xanthos, designed to quantify and analyze global water availability (Zhao, Wild, and Vernon, 2023).[9] Xanthos provides historical data (from 1850 onwards) as well as projections (up to 2100) at high geographic and temporal resolution. Dispatchable hydro capacities are estimated to decline by approximately 20 percent on average by 2050 under a high emission scenario that closely mirrors current trends. The estimates range from 9 to 28 percent from 2030 to 2050. Under mild climate change assumptions, dispatchable hydro capacities would remain broadly similar to current levels but feature higher volatility.

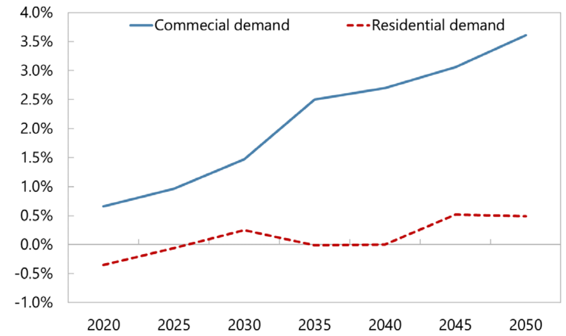


[8] Dispatchable capacity refers to the sources of electric power that can be programmed on demand and dispatched immediately when needed.

[9] Xanthos Output Dataset Under ISIMIP3b Selected CMIP6 Scenarios: 1850 - 2100 (Basin and Regional Scale) (v0.0) [Data set]. MSD-LIVE Data Repository. https://doi.org/10.57931/1923091.

- **Climate impact on power demand.** Total power demand is estimated to increase by 2-4 percent due to changing demands for cooling and heating. Projections on the impact of climate change on power demand were drawn from the projections of the Global Change Analysis Model (GCAM),[10] a market equilibrium model by the PNNL, which is compatible with Xanthos and operates from 1990 to 2100. The model allows to examine sectoral dynamics under various climate pathways and scenarios. The model projection reflects the impact of slow-moving temperature increases and precipitation changes on power demand of commercial and residential buildings, taking into account the evolving demands for cooling and heating. While residential demand is expected to increase in line with the baseline, commercial power demand is set to rise by around 3 ½ percent in addition to the baseline, assuming a high emission scenario that closely mirrors current trends.

Power Demand Change Under Moderate Climate Scenario
(Percent change from baseline)



Source: Fund staff calculations.

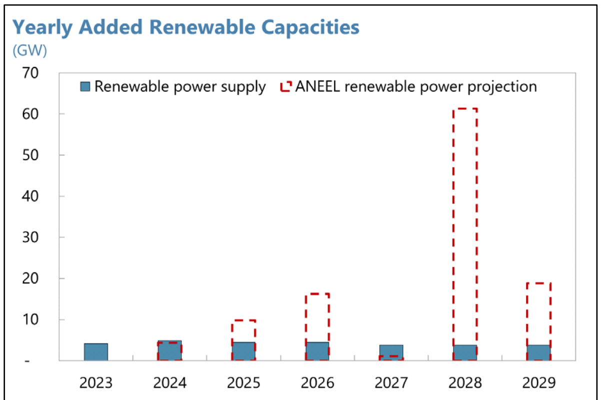
- **Power gaps**. Building on the estimated evolution of hydropower generation and power demand, potential power gaps are computed using an extension of the IMF's Climate Policy Assessment Tool (CPAT). The standard CPAT power demand equation was extended for both residential and service sectors (as part of the commercial sector), to account for the percentage changes in power demand taken from the GCAM. Hydropower generation projections were integrated in CPAT's engineering model algorithm in two steps. First, an upper bound on hydropower generation was introduced by year. Second, the upper bound was parametrized in line with Xanthos's projections, representing the impact of climate change. Third, dispatch decisions on hydropower generation were based on the minimum between the upper bound and the historical capacity factor. To finalize the computation of power gaps, we make the following assumptions on the path of renewables: strictly following the current trajectory of investments in renewables, additional renewable capacity will experience a moderate increase of approximately 2-5 percent compared to the baseline in 2030, bringing cumulatively 28.6 GW new capacity sourced from wind, solar, and other renewables (Figure 4). Under this trajectory, power gaps arise due to hydro deficiency and increasing demand: absent an expansion in power generation, the two latter effects could result in power deficiency up to 82 TWH in 2030 (or 14 percent of the power supply in 2021). The assumed trajectory is rather conservative and describes a lower bound of potential power gaps. Brazil's energy agency ANEEL (Agencia National de Energia Electrica) compiles a pipeline of ongoing investments which are expected to produce additional renewable capacities significantly above these assumptions (Figure 4).

- **Impact on emissions**. At given trajectories, these power gaps may be filled by higher fossil fuel consumption, at least in the short term before significantly scaling up renewable capacities (expected around 2028, according to the ANEEL pipeline). Applying CPAT, which optimizes the fuel mix in the power sector under given cost structures and capacity constraints of Brazil's energy system, the model shows that the demand-supply gap would be covered by a significant share of fossil fuels between 2024 and 2028. Fossil fuel consumption would experience a cumulative increase by 20-70 percent, reintroducing up

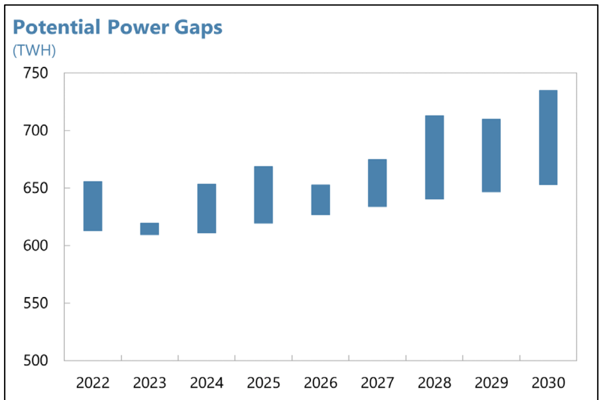
[10] GCAM: Global Change Analysis Model | Global Change Intersectoral Modeling System (pnnl.gov).

to 96 megatons of CO2 into the atmosphere over the same period. This increase in emission is equivalent to around 20% of total emission in Brazil in 2019.

Figure 4. Renewable Energy Pipeline and Potential Power Gaps



Sources: ANEEL; Fund staff calculations.



Source: Fund staff calculations.

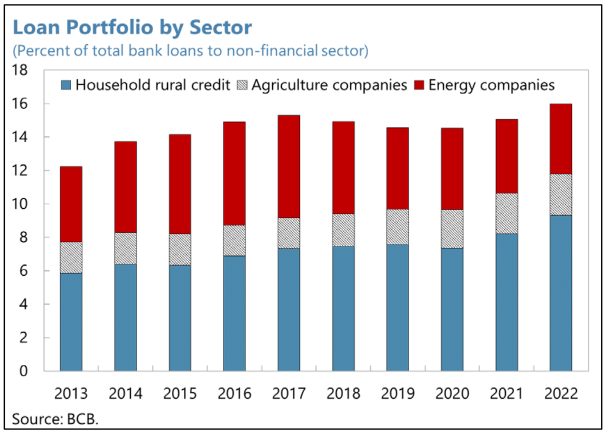
Financial sector

About 20 percent of the financial sector's credit portfolio is exposed to sectors vulnerable to climate change, with the share of agriculture (businesses and rural households) increasing to around 12 percent of total bank loans over the past decade (Figure 5, left). Credit to companies in the energy sector amounts to around 5 percent of GDP (including credit for renewable energy projects), and around 3 percent of GDP finances construction activities. The portfolio exposure is likely a lower bound, given other sectors' sensitivity to climate conditions, including tourism. A mitigating factor could be the short-term nature of the extended credit, in particular in the agriculture sector, which could increase the scope for adaptation.

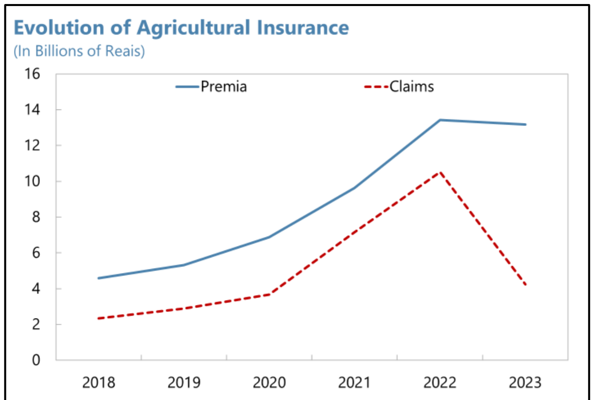
The BCB (2023a) estimates that around 8 percent of the financial sector's credit portfolio is sensitive to transition risks, concentrated on smaller financial institutions, notably lending to the cattle and soybean industry, as well as cargo and transportation. Focusing on physical risks and drought scenarios, the BCB notes that 16 percent of the credit stock is currently with water-intensive borrowers, increasing to 19 percent in 2030. Operations at risk from heavy rainfall events are currently contained but estimated to increase to 16 percent in 2030 and 30 percent in 2050. The 2021-22 drought doubled premia and claims for agricultural insurance contracts offered by the private sector (Figure 5, right). While premia remained above claims throughout, suggesting frequent re-pricing of contracts and a profitable insurance sector, these developments increase the risk that insurers may exit more vulnerable regions, reducing their financial resilience, or that private insurance products become too expensive for lower-income farmers.

Recent regulatory changes by the BCB, which increased disclosure requirements for financial institutions related to qualitative aspects of climate risk in the areas of governance, strategy, and risk management (see section on Brazil's climate strategies), seem to have influenced lending behavior of mainly larger lenders. The latter have started to reallocate their portfolio to less environmentally exposed sectors (Faruk, Pedraza, and Ruiz-Ortega, 2023).

Figure 5. Bank and Insurance Exposure to Climate Risks



Source: BCB.

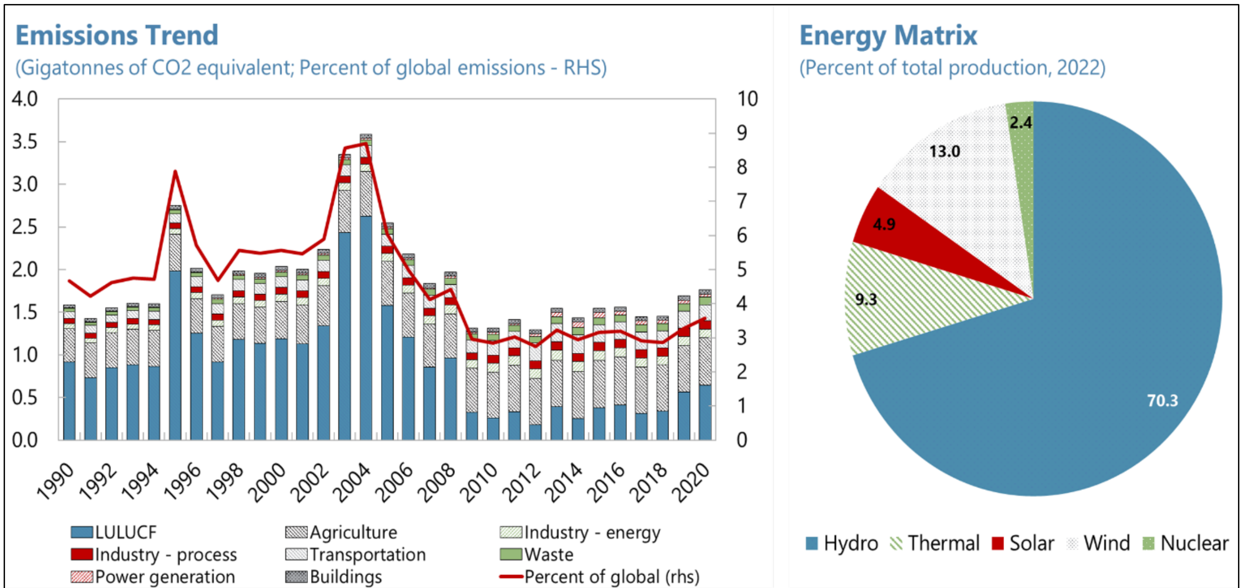


Source: SUSEP.

Policy Options to Strengthen Resilience and Green the Economy

Brazil's carbon emissions account for about 3.5 percent of global emissions despite the very green energy mix (Figure 6). Emissions are concentrated in carbon dioxide (60 percent) and methane (32 percent). Average emissions from 2017 to 2020 were driven by: agriculture (34 percent); land-use change (29 percent, LULUCF); industry (12 percent, of which about half are process emissions); transportation (12 percent); and waste, power generation, and buildings (11 percent combined). The relatively low emissions through power generation are due to the high share of renewables in energy production (see section Key vulnerabilities). Due to a large reduction in emissions from LULUCF, emissions fell by around 2 gigatons from 2005 to 2010, reducing Brazil's share of global emissions from nine to three percent of global totals. Emissions per capita have increased over the past decade from around 3.1 to currently 5.2 tons but are well below the peak level of 11 tons in 2003 and still below the world average.

Figure 6. Emissions and Energy Profile



Source: IMF staff calculations using Ministério da Ciência, Tecnologia e Inovação (Participação de GEE por Setor) using GWP from AR5 and report 6ª. Ed Estimativas (1990-2020).

Brazil's climate strategies

Brazil increased its climate pledges in 2023, returning to its original 2015 target. The updated Nationally Determined Contribution (NDC) commits to reducing emissions by 53 percent below 2005 levels by 2030, covering all major emissions sources (including methane and land-use change), and reaching net zero emissions by 2050. Achieving the NDC requires further lowering deforestation and agricultural emissions, and continuing reductions in transportation and industrial emissions. Brazil will need to reduce 2020 emissions by 28 percent by 2030 to achieve its NDC.

Important progress has been made in addressing both climate vulnerabilities as well as seizing opportunities of a green transition. The Ministry of Finance's Ecological Transformation Plan aims to steer green growth by enhancing technology and productivity in a green and equitable way, while decarbonizing the economy. The plan comprises six pillars and is being implemented in close cooperation with other ministries:

- Promoting **green finance** by operationalizing the mandatory Emissions Trading System (ETS), which establishes a cap-and-trade system targeting emitters that release more than 25,000 tons of CO2 equivalent annually, a green taxonomy, regular issuances of green and social bonds (with the first issuance taking place in November 2023), and green financial regulation;
- Enhancing **productivity** through green R&D and its transformation into businesses, including by leveraging funds from the oil sector for the transition and incentivizing credit allocation;
- Shaping a "**bio economy**" via integrating agricultural production with forest protection including through ecotourism, biotechnologies, and payment for environmental services;

- Accelerating the **energy transition** by becoming an exporter of energy with green hydrogen, building on Brazil's success in using ethanol in the transport sector, including from biomass, and investing in energy storage;
- Leveraging the **circular economy** by using waste and sewage systems to produce electricity; and
- Building **resilient infrastructure** to deal with climate shocks and restore climate justice for poorer households.

The Banco Central do Brasil's (BCB) Sustainability Agenda is well-advanced, covering regulation, supervision, policy design, as well as internal measures and research. The agenda aims to incentivize the financial system to offer more favorable conditions for sustainable operations, while maintaining the focus on financial stability and resilience. The Agenda comprises:

- **Regulation**. Following the Network for Greening the Financial System's recommendations, the BCB has been working on incorporating sustainability aspects into prudential regulation. In a first step, financial institutions were asked to disclose qualitative aspects of climate risk related to governance, strategy, and risk management. In a second step, from end-2023 onwards, disclosure is expanded to quantitative aspects, including metrics and targets, mapping exposures to climate-related transition risk and voluntary decarbonization targets by financial institutions. Risk assessment regulation also requires financial institutions to include both physical and transitional risks in their integrated management framework, applying stress testing, risk appetite statement, and board involvement to social, environmental, and climate-related risks.
- **Sustainable Rural Credit Bureau**. Established in 2022, one of the objectives of the BCB's green credit bureau (Sicor) is to bring more information and transparency to the rural credit system and to foster the conditions for a "greener" agriculture. Sicor focuses on agribusiness and registers about 2 million rural credit operations per year, corresponding to R$300 billion (about 3 percent of GDP). The bureau enables beneficiaries of rural credit to make their registered information available to any interested party without the need of intermediation by financial agents. It also allows the BCB to effectively monitor projects and block directed credit to those that are non-compliant with social and environmental regulations, including by preventing farming credit operations in protected lands.
- **Supervision**. Information collection on climate risks is being enhanced with the objective of a broad mapping of social, environmental, and climate aspects associated with credit and securities operations recorded on the balance sheet of financial institutions. The exposure to physical risks was assessed through sensitivity analyses of the credit portfolio with respect to extreme drought (BCB, 2022) and heavy rainfalls (BCB, 2023b).
- **Central Bank Operations**. The BCB further pursues ongoing initiatives on greening their own balance sheet by including sustainability criteria in the selection of counterparties. The BCB is also considering a liquidity facility that would offer preferential conditions to bonds based on Environmental, Social, and Governance (ESG) criteria. The Digital Real initiative could also offer opportunities to further develop financial instruments that support the Sustainability Agenda, for instance by encouraging the tokenization of ESG financial assets.

Boosting the Amazon's Resilience

Background

In 2020, natural forests and plantations covered approximately 500 million hectares, or 60 percent of Brazil's national land area. Over 40 percent of the forest area consisted of primary forests and less than 2 percent managed plantations—Brazil has the highest number of tree species in the world, at over 9,000. The forest sector contributes about 7 percent to GDP, with primary export markets for Brazilian wood products including Argentina, China, Italy, and the US.[11]

Table 1. Mitigation Commitments for Selected Large Deforestation Emitters

Country	Latest NDC mitigiation pledge[a]	Objectives and measures for forestry	Percent of global GHG from deforestation, 2018-2022
Brazil	Reduce GHGs 37% below 2005 by 2025, and by 50% below 2005 levels in 2030.	Zero deforestation by 2030.	37.8%
Indonesia	Reduce GHGs 32% (43**%**) below BAU in 2030 by 2030.	Ban on primary forest clearance; reduce deforestation/degradation; restore ecosystem functions; sustainable forest management.	21.2%
Bolivia	Increase renewable energy share to 79% in 2030 (50% of installed capacity).	By 2030, reduce deforestation to 80% compared to the baseline and in National Protected Areas to 100%.	6.0%
Malaysia	Reduce GHG/GDP intensity 45% by 2030 relative to 2005.	Measures to promote forest carbon storage not specified.	5.4%
Laos	Achieve 60% GHGs reduction compared to BAU by 2030.	Increase forest cover to 70% of land area.	4.9%
Myanmar	Targets for renewables and energy efficiency.	Target to reduce deforestation by 25% (50%) by the year 2030.	4.3%
Cambodia	Reduce GHGs 42% below BAU by 2030.	Halve the deforestation rate by 2030.	2.5%
Paraguay	Reduce GHGs 10% (**20%**) below BAU in 2030 by 2030.	Laws prohibit conversion of areas with forest in the Eastern Region.	1.9%
Peru	Reduce GHGs 20% (**30%**) below BAU in 2030 by 2030.	Measures to promote forest carbon storage not specified.	1.1%
Mexico	Reduce GHGs 35% (**40%**) below BAU in 2030 by 2030.	Achieve zero net deforestation by 2030.	0.4%
Madagascar	Reduce GHGs (**32%**) below BAU by 2030 with over half of reduction from forestry.	Restoration of 55,000 hactares of forests and mangroves by 2030	0.1%
Ecuador	Reduce energy GHGs 20.4-25% (**37.5-45.8%**) below BAU in 2025.	Implement the REDD + Action Plan of Ecuador.	0.0%

Source. UNFCCC (2023) for details on pledges and WRI (2023) for emissions shares.

Notes. [a] Where applicable, more ambitious targets conditional on external finance are in parentheses. Other large emitters include Canada, Russia, and the USA.

Rates of deforestation in Brazil declined from an annual average of 2.3 million hectares per year from 1990-2010 (mostly to support low intensity cattle ranching) to 1 million hectares per year between 2010-2015, though in the last few years until 2023 deforestation has increased with more illegal logging and land conversions to agriculture.[12] Indeed, Brazil contributed the most to global CO_2 emissions from deforestation between 2018 and 2022—38 percent, while the next largest contributors were Indonesia (21 percent), Bolivia (6 percent), Malaysia

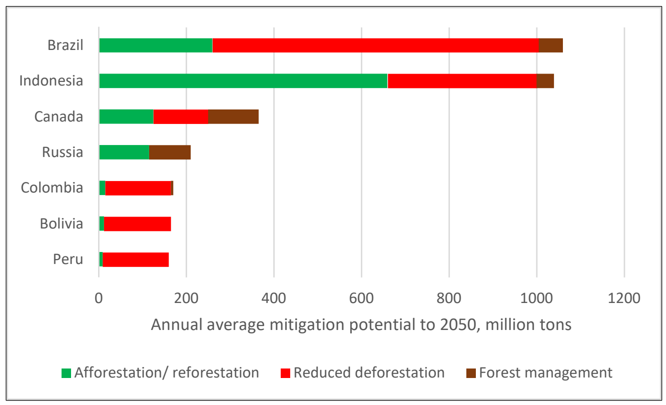
[11] Figures in this paragraph are from FAO (2016, 2020), SFB (2019), UNEP (2020).

[12] See Figure 6 above and WBG (2023).

and Laos (5 percent each). In 2023, impressive progress has been made in the fight against illegal deforestation and the deforestation rate fell by half in the Amazon biome, with some intensification in the Cerrado biome. Some, but not all, large forestry emitters have adopted quantitative targets for reducing deforestation or increasing afforestation/reforestation—Brazil's goal to eliminate deforestation by 2030 is among the most ambitious targets (Table 1). Brazil's recently updated *Action Plan for Deforestation Prevention and Control in the Legal Amazon* (PPCDAm) 2023-27 specifies policies towards reaching this goal.

Roe et al. (2021) suggest that Brazil has the potential to reduce CO_2 emissions from forestry by around 1 billion tons a year on average between now and 2050 with options that cost less than $100 per ton reduced. About three quarters of the opportunities are from reduced deforestation and one quarter from reforestation/afforestation—changes in farm practices at managed tree plantations have only very limited potential for cost-effective reductions. As most current deforestation in Brazil is illegal, eliminating illegal deforestation would achieve most of the emissions reductions.[13] Aside from Indonesia, cost effective mitigation potentials are on a much smaller scale in other countries (Figure 7).[14]

Figure 7. Cost Effective Mitigation Potential, Annual Average to 2050



Source: Roe et al. (2021). Note: Cost effective refers to emissions reductions that can be achieved with average costs of up to $100 per ton CO_2 reduced.

Building on Ongoing Initiatives

Land tenure and subsidies. The authorities are attempting to reform processes for securing land tenure that have been encouraging illegal deforestation. Recent laws have allowed farmers and other occupiers of undesignated public lands to clear the land (usually native forest) to acquire tenure rights for the land in exchange for payments which have often been well below market values (World Bank 2023). In 2019, there were about 32,000 parcels of land, accounting for nearly 9 million hectares in the Brazilian Amazon, that were being processed for land titles. Besides ending impunity of fines for illegal deforestation and reversing authorization for illegal mining in the Amazon, other efforts could include reforming incentives to deforest that come from existing subsidies, rural credit policies,[15] and the structure of the rural land tax. Tax breaks for

13 Brito et al. (2019), Koch et al. (2019).

14 Another recent study (World Bank 2023) suggests Brazil can achieve zero illegal deforestation by 2030 without harmful effects on GDP or export revenues. This would however require a comprehensive policy approach with effective enforcement of forest law and incentives for forest conservation, afforestation/reforestation, and higher agricultural productivity.

15 Plano Safra, the main subsidized credit program, supports cattle ranching in the Amazon's less developed states and crop production in the more advanced states (World Bank 2023).

agriculture have increased from 9 percent of total tax breaks in 2006 to 12 percent in 2021. As the land tax rises with farm productivity, it encourages low intensity cattle ranching.

Monitoring systems for timber and land use. Partly in response to legislation in timber-importing countries, there has been increased demand for traceable timber, requiring importers to prove their timber purchases are legal. In response, various state-level governments and the Federal Government of Brazil have developed traceability systems to track timber flows from harvesting and processing to the point of sale and the final consumer.[16] Indeed the Brazilian Forest Service has been developing timber traceability systems using remote sensing to monitor and verify forest management practices and supply chains originating in federal forest concessions.[17] All roundwood can now be traced back to the stump, and products that have undergone primary or secondary processing can be linked to the facilities and businesses where the transformation took place, and to a list of forest management units from where they originated—some processors however view reporting requirements as onerous. Building on these advances, mapping untitled public lands would provide the Government with data to facilitate their designation as protected areas and help determine which public lands could be designated for private use. Modernization of the land registration would facilitate the implementation of incentives schemes for land conservation discussed below.

Amazon Fund. This fund was created in 2008 to support sustainable forestry projects in the Brazilian Amazon but projects were halted in 2019. In 2023, the Amazon Fund resumed projects, focusing on efforts to halt illegal deforestation. The PPCDAm 2023-27, which includes satellite imaging to counter land grabbing as well as investment in the bioeconomy to develop the Amazon region, will guide the Amazon Fund's projects in coming years. Granting access to private sector participants could enhance the Fund's effectiveness.

Carbon credits. The government has been offering concessions for publicly owned forests for sustainable logging under a program operating since 2006 but only 1 million out of 43 million hectares of eligible public forest are currently leased under the program.[18] The Brazilian Congress recently passed a bill allowing companies with forestry concessions to generate carbon credits for forest preservation, which could be sold in the country's carbon market, potentially generating revenues upwards of $25 million a year.[19] Cross-country evidence on challenges with rainforest carbon offsets shows the importance of putting in place strong safeguards which ensure transparent accounting on how credits are calculated.

Private Sector Initiatives. Scaling up private sector policies such as Zero-Deforestation Commitments (ZDCs)—which bar suppliers who produce goods on recently deforested areas—could further enhance incentives for forest protection. For example, the 2009 G4 Agreement by the three largest international meat-packing

16 Civil society organizations can play a complementary role, for example, organizations like BVRio Institute and Imaflora take government timber traceability information and make it available to international buyers through online platforms. See WRI 2023 for further discussion of timber tracking systems in Latin America.

17 IBAMA (2019).

18 https://carbonherald.com/brazil-forestry-bill-to-allow-carbon-credits-from-concessions.

19 Estimated by Instituto Escolhas based on a sample of 37 potential forest areas for leasing.

companies in Brazil[20] established deforestation cut-off dates for their suppliers after which new deforestation results in exclusion from their supply chains. One study suggests the initiative reduced cattle-driven deforestation by 15 percent in the Amazon between 2010 and 2018.[21] There are limits on the effectiveness of ZDCs, however. For example, they do not cover small-scale packagers or much of the production for domestic consumption—and they do not provide incentives for afforestation/reforestation. In addition, they do not cover indirect supplies—cattle that were raised and fattened on other farms before being sold to ranchers covered by ZDCs. Still, ZDCs could be scaled up through more comprehensive monitoring of direct and indirect suppliers and assistance for farmers to shift to legal, deforestation-free production.

Payments for Environmental Services (PES) Programs

Fiscal measures targeted at land conservation may be a practical and politically feasible solution for addressing land use and agricultural emission efficiency for the near term, such as a Payment for Environmental Services (PES) program—Costa Rica has pioneered this approach (see Box 1). Under this scheme, landowners bid for contracts paying them for habitat restoration or preservation projects with payments linked to various environmental services like carbon sequestration, habitat value, and water protection. For example, measurement of carbon sequestration could build off monitoring capacity being developed under the REDD+ Readiness Program.[22] Landowners who anticipate receiving payments could be supportive of the program.

Some refinements could be considered if a PES scheme were to be introduced in Brazil including:

- *Targeting*: Linking part of the payments to an environmental index that ranks local areas according to ecological value (e.g., biodiversity corridors)—this would target payments for land areas that are most valuable from an environmental perspective.
- *Contracts*: Allowing for long contracting periods, or contract renewals, to reduce risks that habitat restoration or preservation will be reversed in the future.
- *Complementary measures*: Combining the scheme with regulations or taxes to discourage land clearance to reinforce overall effectiveness.
- *Fiscal*: Limiting fiscal costs of the program by redirecting funding from the current farm supports or, again, reinforcing the PES with taxes on forest clearance.

[20] JBS, Marfrig, and Minerva, who account for more than 70 percent of cattle sales. These large multinational firms with public profiles were susceptible to pressure from environmental groups like Greenpeace and had the capacity to implement monitoring and exclusion mechanisms. See Grabs et al. (2021).

[21] See Levy et al. (2023). The agreement requires supplying ranchers to enroll on a public environmental registry, which identifies the boundaries of their ranches and enables monitoring of changes in forest cover.

[22] This is a cross-country initiative, administered by the World Bank, to Reduce Emissions from Deforestation and forest Degradation, and foster conservation, sustainable management of forests, and enhancement of forest carbon stocks. See www.un-redd.org. In the past, a challenge for project-based approaches to reducing forestry emissions has been the need for projects to demonstrate additionality. With periodically updated carbon inventories under REDD+ there is no need to assess additionality as the baseline against which changes in emissions are calculated is already available.

Bottom-up, project-by-project based approaches, on the other hand, may face significant limitations as various obstacles may constrain their effectiveness, cost-effectiveness, and scaling up:

- *Effectiveness*: Contracting for projects on a landowner-by-landowner basis (which requires experts trained in forestry to evaluate projects, and national governmental organizations supporting the project) imply significant administrative costs. High transactions costs may also preclude smaller-scale landowners. Leakage within national borders may also be significant because there would be no penalties for landowners outside of the contracting process deforesting in response to program-induced changes in agricultural or timber prices.
- *Cost effectiveness*: Under bottom-up approaches there is no automatic mechanism for equating explicit or implicit prices on CO2 emissions or other environmental indicators across landowners and projects so there is no guarantee that the most cost-effective projects are prioritized.
- *Scaling up*: Fiscal constraints may limit the size of the program given the need to finance each project from domestic revenue sources.

Box 1. Costa Rica's PES Program

Costa Rica has pioneered a Payments for Environmental Services program over the last 20 years providing, on a project-by-project basis, cash payments per hectare to private landowners for five- or ten-year contracts. These payments compensate landowners for:

- carbon sequestration;
- protection of water catchment areas for urban, rural, and hydroelectric plant use;
- protection of biodiversity (for ecosystem preservation, scientific research, the pharmaceutical industry); and
- protection of natural landscapes (for tourism and scientific purposes).

The program has been predominantly financed by a 3.5 percent sales tax on fuel use, though the objective is that beneficiaries of environmental services (for example, water users) eventually pay for the services they receive.

Some challenges with the program include:

- *Effectiveness*: Most of the dramatic increase in forest coverage in Costa Rica occurred prior to the establishment of the PES—the program was in part compensating for a 1995 law prohibiting the clearing of most forest lands for commercial purposes. Contracts can be renewed, though this is not a requirement, and landowners are free to deforest their land after a contract has ended.
- *Coverage*: Many small and medium farmers are precluded from the PES program because of limited funding, or insecure land tenure—indeed approximately 8,000 property owners representing only 11 percent of Costa Rica's national territory is protected by the plan. A new PES scheme aimed at farm owners with 10 hectares or less is, however, currently underway.
- *Targeting*: The program does not target high priority lands, such as biological corridors—given its voluntary nature. Participants can be enrolled who self-select low priority lands at low risk of deforestation or lands that are already legally barred from deforestation.
- *Fiscal costs*: The program imposes a fiscal cost on the government (currently about 0.2 percent of GDP).

Sources: www.fonafifo.go.cr/en; and Carter (2020).

Feebates[23]

Feebate schemes can provide more comprehensive incentives than PES programs while also avoiding a new fiscal cost—but they are a longer-term option, that could ultimately build off a PES type scheme. Prerequisites for establishing a feebate program include secure property rights for covered land area, capacity for monitoring environmental indicators and applying incentives, and improving governance.[24] A feebate scheme would cover large landowners at the forestry/agriculture border, with fees on landowners converting forest land and subsidies for putting farmland into conservation and restoring habitat. The discussion here focuses on feebates linked to carbon sequestration though more generally they could be linked to other environmental indicators. Annex 1 provides more detail on design issues.

Feebates have several attractions as they:

- *Exploit all potential opportunities* for promoting forest carbon storage on private land, and possibly public land subject to private harvesting. With landowners penalized or rewarded according to behavioral changes affecting carbon storage, they have incentives to increase storage through afforestation/reforestation, reduced deforestation, and changes in forest management. Landowners in all regions of the country face these incentives, which addresses leakage risks at the national level. In principle, feebates can also be built into concessions granted to private entities harvesting timber on public lands.
- *Are cost effective.* Feebates provide the same reward for an extra ton of stored carbon across behavioral responses and landowners (and timber harvesters on public lands)—this promotes equalization of incremental mitigation costs across mitigation opportunities and regions.
- *Avoid large fiscal costs* as they can be designed to be approximately revenue neutral (Annex 1).
- *Are, from a technical perspective, straightforward to scale up.* The carbon storage price in the feebate can be ramped up over time in line with emissions objectives for the forestry sector.

New Zealand has implemented a nationwide pricing scheme incorporating the forestry sector, providing a precedent for addressing administrative and practical issues in designing similar pricing schemes for forestry in other countries—see Box 2.

23 The discussion here is based on Parry (2020).

24 In some areas, criminal activity surrounding illegal deforestation makes it difficult for government officials to operate (“rainforest mafias”, Acebes and Wilkinson 2019). Control and law enforcement in these remote areas would need to be re-established before implementing comprehensive policies.

Box 2. New Zealand's Pricing Scheme for Forestry

New Zealand is the first country to implement a nationwide pricing scheme for the forestry sector through its emissions trading system (ETS) covering energy, waste, and forestry. Landowners implementing afforestation/reforestation projects can be eligible for credits which can be sold on the allowance market while landowners must purchase allowances if there is deliberate or accidental deforestation on their land.

ETS forestry participants are entitled to receive one carbon credit or New Zealand Unit (NZU) per ton of CO2 removed as the forest grows each year for registered post-1989 forest land, for either introduced or native species. To be eligible for credits, landowners must convince regulators that the forest will reach 30 percent canopy cover and 5 meters in height within a reasonable time period. Forest owners also need to repay their units earned if the forest is harvested or if they exit the scheme. For illustration, for a plot of 10 hectares planted in 2022, (fast-growing) pines would earn an average of around 220 credits per year through to 2050, exotic hardwoods around 200 credits per year, and native forest about 75 credits a year.

There are two situations when land can be considered deforested. First the land is converted for example to land for pasture or housing. Second, the land does not meet certain criteria within set time frames (e.g., for stocking rates per hectare and growth rates of trees on the land).

Sources: www.mpi.govt.nz, www.carboncrop.nz.

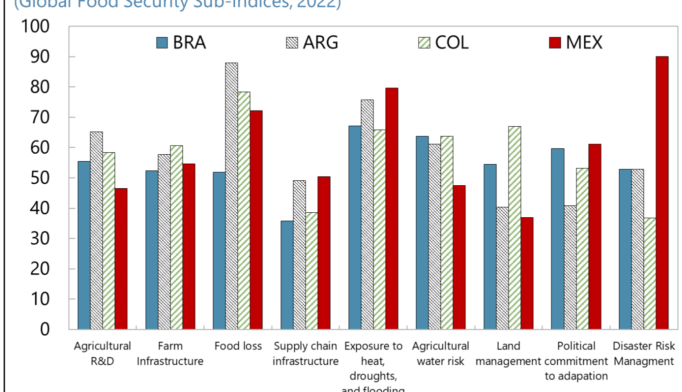
Investing in Climate-Smart and Sustainable Agriculture

Brazil has a long history of regional programs to promote climate-smart agriculture (e.g., Adapta Sertao, MAIS, and ABC CERRADO) and has made substantial progress over the last decade in almost all categories of food security.[25] However, Brazil's agricultural sector still lags regional peers in certain aspects of adaptation capacity, in particular regarding food loss, farm infrastructure, and supply chains (ND-GAIN, Food Security Index, see text chart). Building on recent improvements, it would be important to continue scaling up existing good practices through targeted and better-structured support and more investment. Adaptation policies could focus on:

- Agricultural infrastructure, through investments in irrigation systems; soil and water resource management; and food loss reduction.

Selected Indicators on Agriculture Adapatation

(Global Food Security Sub-Indices, 2022)



Source: Corteva, Global Food Security Index

Note: Higher values correspond to less vulnerability.

[25] Brazil shows significant improvement in almost all categories of the Global Food Security Index between 2012 and 2022, with the largest gains in agricultural R&D (plus 29.6 points), farm infrastructure (plus 32.8 points), and disaster risk management (plus 52.9 points).

- Technology and innovation, through investments in R&D targeted to climate change impacts; and knowledge management and information-sharing system, especially for small- and medium-scale farmers.

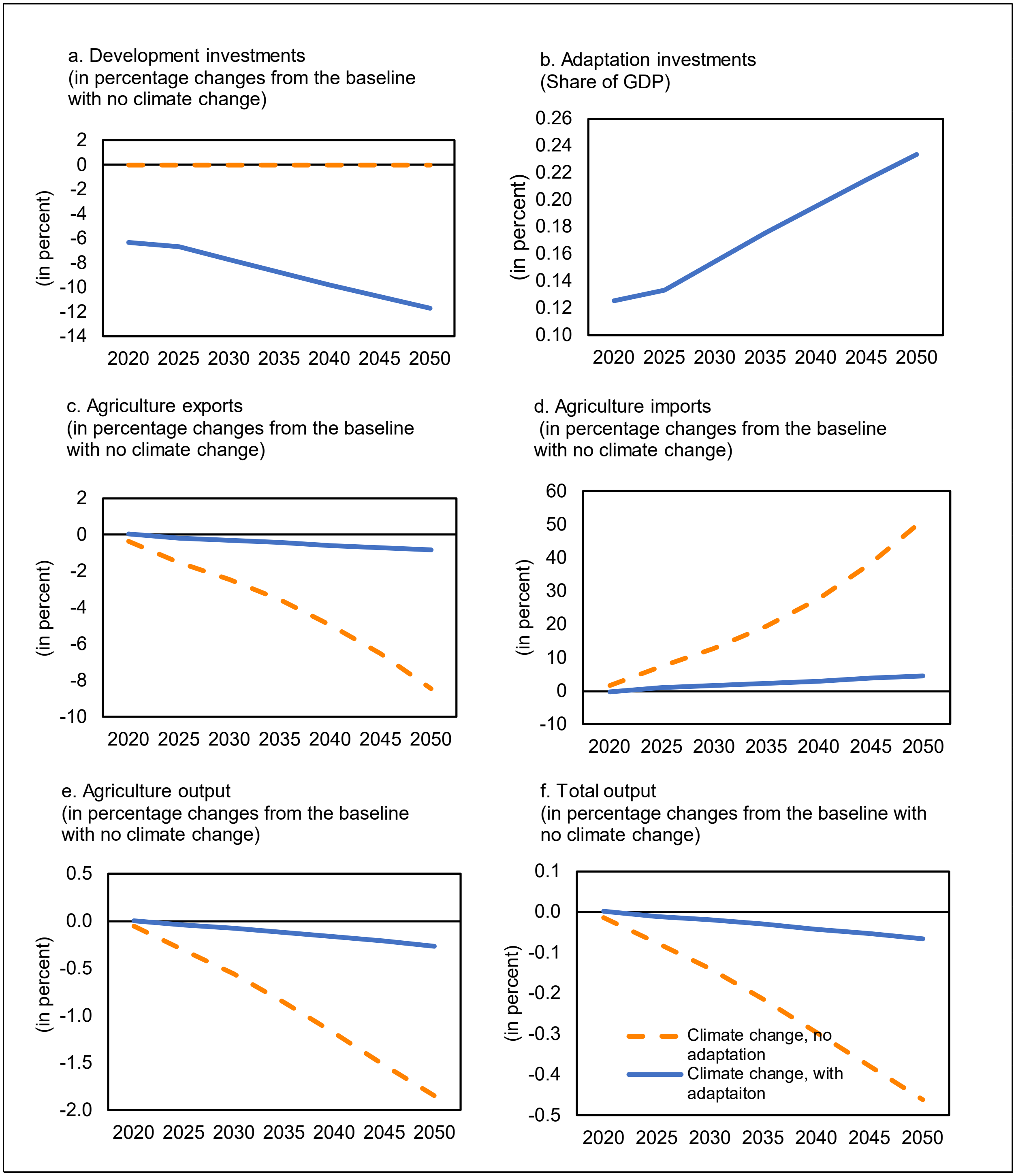
Optimizing adaptation investment

Adaptation investment in agriculture is necessary to mitigate production losses due to climate change and maintain food security. Chen, Kirabaeva, and Zhao (2024), show that the optimal amount of investment in adaptation helps reduce climate change damages to agriculture productivity in a cost-efficient manner. Underinvesting in adaptation would require (much) higher investment spending on agriculture development to offset the production loss from climate change. Improving total factor productivity (TFP) and adaptation efficiency further enhance adaptation investment and maintain food security. However, excessive adaptation investment could be wasteful, which is particularly relevant under tighter budget constraints. Trade openness helps mitigate the climate change impacts on food security.

The underlying model builds on a two-sector open-economy (agriculture and non-agriculture), with international trade of agricultural and non-agricultural goods between the home country and the Rest-of-the-World. The model presents two types of public capital stocks in the agricultural production: development capital and adaptation capital. Agricultural production is subject to climate damage through productivity losses.

Applying the model to the case of Brazil, we show that underinvesting in adaptation would require over 10 percentage points more in public investment for broader development (in 2050) compared to a scenario with optimal investment in adaptation (difference blue and orange lines in Figure 8a), to offset climate change damages on agricultural output. The model results suggest that adaptation investment needed in addition to standard development investment is in the range of 0.1-0.3 percent of GDP per year between 2025 and 2050 (see Figure 8b), depending on climate scenario, trade costs, and other uncertainties, and assuming moderate budget constraints. With no financing constraints, optimal adaptation levels increase to 0.25-0.5 percent of GDP per year by 2050. In the event that adaptation investments be insufficient, trade openness could provide a buffer to maintain food security. Without adaptation, domestic agricultural production would fall by up to 2 percent and agriculture imports would increase significantly (from 3.9 to 5.9 percent of GDP or by about 50 percent), acting as an insurance against adverse climate change impact on food production and consumption (see Figure 8d).

Figure 8. Climate change impact on agriculture output and trade with and without adaptation investment in percentage changes from the baseline with no climate change.

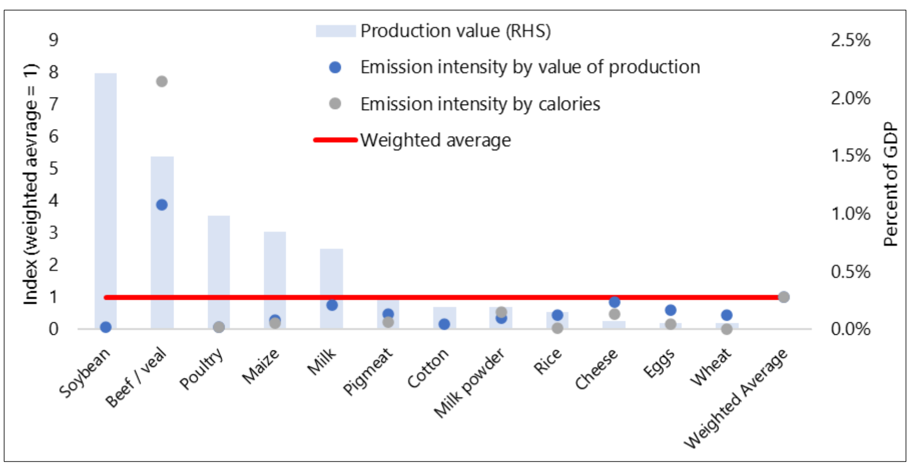


Improving emission intensity

Fiscal incentives could further help promote sustainable farming, with a feebate possibly preferred as it limits fiscal costs and can be designed to address competitiveness concerns. The feebate could apply to large farmers and rely on emissions measured using a proxy approach based on a farm's inputs (such as feed and fertilizer use and type, production, and acreage) potentially similar to that under IPCC reporting standards (Parry and others, 2022). It would complement existing subsidy programs, such as the ABC+ that now explicitly links subsidies to farming sustainability, to provide a reinforcing incentive to reduce agricultural emissions. Denmark has introduced legislation of a similar scheme, and it has been strongly considered in New Zealand.

The design of a feebate scheme would need to consider the differences in emission-intensity of producing different agricultural products, as well as how emission-intensity is defined, as this has implications for environmental effectiveness and competitiveness. Estimates from the OECD-FAO suggest that emission-intensities vary substantially across products and depend on the definition used (Figure 9).[26] When emission-intensity is defined as emissions per production value, emissions from beef and veal production are estimated to be four times above average emissions (and 55-60 times that of soybeans and poultry), while they are 7.7 times above average based on emissions per calorie of output (110 times that of poultry; data on calories for soybeans is not available). Using production value to define emissions-intensity is most economically efficient as producers are incentivized to increase output and shift to more valuable products, although it does create potential transfer pricing risks (around the value of output for related party sales).

Figure 9. Emission Intensity Across Products and Definitions



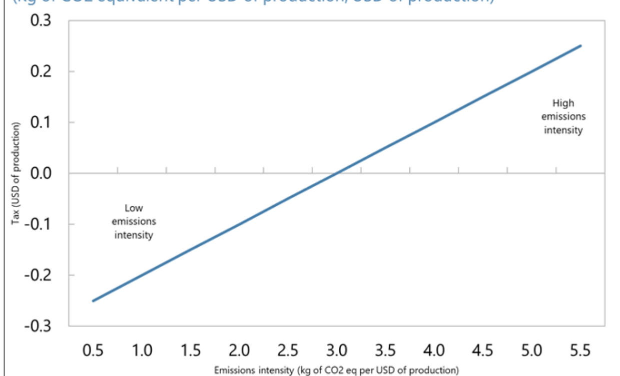
Source: OECD-FAO Agricultural Outlook database.
Note: Data on calories is missing for soybeans and cotton.

[26] While there are uncertainties around the exact level of emissions from agriculture, and particularly cattle, several studies suggest that cattle emissions make up a majority of Brazil's total emissions (SEEG 2023, ClimateTrace 2023). Cattle production is known to be more carbon intensive than other agricultural products (WRI 2016).

A pure feebate that covers all agricultural products and links fees/subsidies directly to emissions-intensity would provide the strongest incentivize to reduce domestic emissions—this provides incentivies to switch from high to low emitting products and lower emitting processes within a products. On average and before considering behavioral responses, it would result in higher taxes on beef/veal, no effect on milk and cheese, and subsidies for other production. Alternatively, feebates could be applied at the product-level (i.e., with the pivot point set at the average emissions-intensity to produce a given product)—this encourages switching to lower emissions-intensity processes for a given product but not switching across products so is less effective in reducing emissions but potentially more politically acceptable and less susceptible to leakage. Under either scheme, there would be a strong incentive to invest in research and development to reduce emissions, which could have spillovers to other firms as well as create the potential for new exports for producers. Emission-reduction technologies, including nutrients for lower methane emissions by cattle, could also ensure that Brazil's agricultural exports remain cost-effective and globally competitive.

Average Emissions Intensity and Feebate Level

(Kg of CO2 equivalent per USD of production; USD of production)



Source: Fund staff calculations.

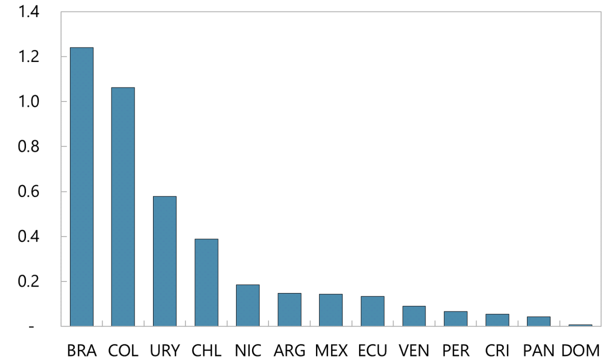
Diversifying Power Generation Sources

While hydropower remains the largest energy source, solar and wind electricity production has rapidly expanded in the past years, now representing, together with biomass, about 20 percent of total electricity generation, from close to zero 20 years ago. The expansion in solar and wind capacity has almost exclusively been financed through private investments and without subsidies, reflecting highly advantageous capacity factors. In line with these developments, jobs created in Brazil's renewable sector outpaced regional peers, though remain relatively low skilled.

Brazil's potential for energy from wind, solar and biomass is large, as also reflected in an impressive project pipeline. Over 111 GW non-hydro renewable capacity is projected to come on stream between 2024 and 2030,[27] which is more than enough to meet higher future demand and fill power gaps (see section Key Vulnerabilities) – and avoid higher fossil fuel consumption in the short term, creating opportunities for energy export, including through green hydrogen. Addressing infrastructure bottlenecks is needed to deliver on the planned expansion of renewable energy and handle increased weather volatility.

Jobs in Renewable Energy Sectors

(Percent of total labor force, 2021)



Sources: IRENA; Fund staff calculations.

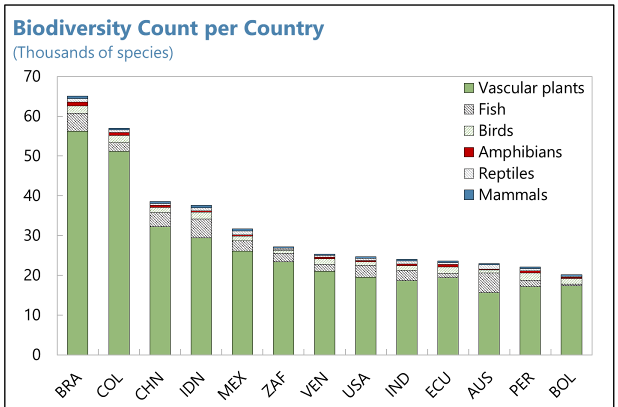
- *Strengthening the grid and cross-border connections to alleviate infrastructure limitations*. More decentralized power generation, varying availability of wind and solar (which benefit from priority in the grid), as well as increased temperature and precipitation volatility, challenge effective distribution through the existing grid. Investments are needed to respond to these demands and secure the investment pipeline.28
- *Maintaining hydro capacity and expanding energy storage*. Solar and wind energy need to be paired with sources of reliable baseload such as hydropower (Wasti et al 2022). Investment plans could include capitalizing and retrofitting existing dams and hydro plants with more flexible design such as incorporating pumped storage. This could help make up for the generation losses brought by climate change without entailing significant investment and environmental costs of building new dams. Alternative storage facilities, including batteries and hydrogen, are being considered.
- *Mainstreaming climate risk management into energy sector planning*, including monitoring and response systems to adjust hydro supplies and meet power demands.

Leveraging Opportunities for Green Growth

[27] Agencia National de Energia Electrica (ANEEL).

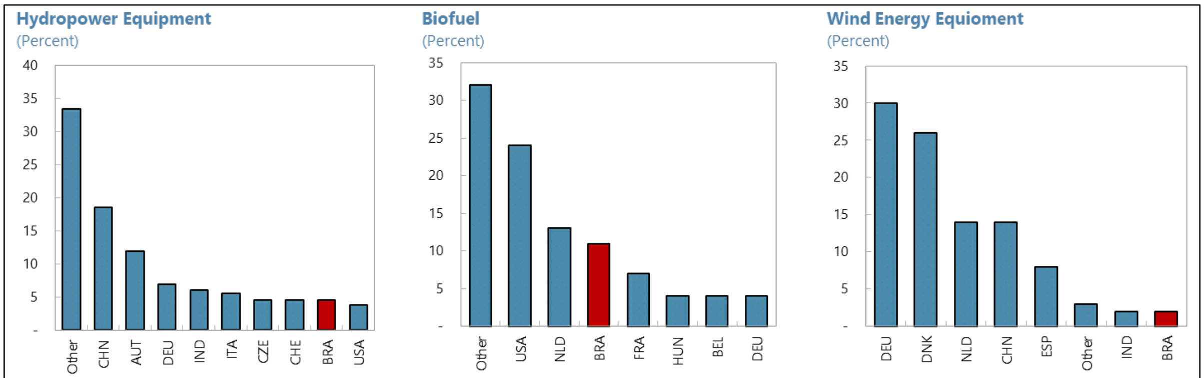
[28] The likelihood of realization of the pipeline's investments as collected by ANEEL depends on improvements in grid infrastructure.

Brazil could build on its relatively green energy mix to step up export-oriented manufacturing and seize growing demand for green goods and services. Further expansion in renewables could allow for production and export of energy, for instance via green hydrogen. Brazil also holds a competitive advantage in some key green industries (Figure 10), such as biofuel production[29] (11 percent global market share[30]) and hydropower equipment (4½ percent global market share). Brazil is topping biodiversity indices worldwide and could leverage this potential as input to R&D. Finally, transferability of technology between oil and gas and renewable energy, particularly offshore wind, could be explored more broadly.



Source: Mongabay, using data from World Conservation Monitoring Centre of UNEP, 2004; Fishbase; Birdlife International; AmphibiaWeb; IUCN; and Reptile Database.

Figure 10. Brazil's Global Market Share in Selected Green Industries



Sources: Amir Lebdioui: "Greening Economic Development", with data from OEC, UN Comtrade, IMF Climate data monitor and EurObserver'ER, and ITC.

To further green the economy, Brazil has recently approved the legal framework for a mandatory ETS,[31] which establishes a cap-and-trade system targeting emitters that release more than 25,000 tons of CO2 equivalent annually. Entities responsible for emissions over 10,000 tons of CO2 per year will be required to report their emissions. Around 5000 companies are currently emitting above the cap of 25,000 tons and will be mandated to purchase Brazilian Emissions Quotas (CBE), representing an allowance to emit one ton of CO2 and Verified

[29] Trade regulations imposed by other countries risk hamper further expansion in this market.

[30] Lebdioui (2022), based on OECD, UN Comtrade, IMF Climate data monitor and EurObserver'ER, and ITC databases.

[31] Sistema Brasileiro de Comércio de Emissões de Gases de Efeito Estufa – SBCE.

Emission Reduction or Removal Certificates. Although primary agricultural production has been exempted, some large meatpackers would be included. The market would take about three years to become operational.

The ETS has been designed broadly following international best practice, albeit achieving cost-efficiency calls for encompassing all sectors and greenhouse gases. Administrative constraints make it challenging to include forestry and methane from agriculture, a key consideration in Brazil since most emissions come from these sectors. Allowing for forestry offsets, as currently under consideration for a share of the market, requires robust rules and monitoring of whether afforestation delivers additional, long-term GHG removal--without such a system, offsets can result in a net increase in emissions (World Bank, 2018) and undermine the ETS. In addition, offsets may constrain allowance prices in the ETS, and the resulting price signal for low carbon investments. Finally, price stability mechanisms, such as a price floor or program to purchase surplus allowances, can increase certainty over future prices and support the use of overlapping mechanisms.[32,33]

For its operation, the ETS can draw further lessons from international experience where ETSs have been in place for longer, with the EU, South Korea, and California being some of the most prominent. These ETSs vary in coverage (e.g., the EU's covers primarily CO2 from industry and power, while California's and Korea's covers all GHGs from most major sectors), while all have mechanisms to reduce price volatility and increase the effectiveness of overlapping policies, clear pathways for reductions in emissions allowances (e.g., California's will restrict emission to 80 percent below 1990 levels by 2050), and expanded their coverage over time (e.g., the EU is introducing an ETS covering buildings and transportation by 2028). They caution against the use of nature-based offsets—this is not allowed in the EU's ETS, removed from California's as of 2021 due to a lack of effectiveness, and limited in Korea. The schemes have also included measures to address competitiveness concerns, for example, through free allowance allocations to vulnerable firms in the EU which are being replaced by a broader carbon adjustment mechanism imposing charges on carbon embodied in steel, aluminum, cement, fertilizers, and electricity.

Conclusion

Brazil's main vulnerabilities to rising temperatures and changing precipitation patterns are concentrated in agriculture and power generation. Past land-use patterns have been magnifying climate risks for Brazil's biomes, but also for both sectors by profoundly affecting water cycles. Impressive strides have been made in halving deforestation rates in 2023 and important policy initiatives are underway to boost resilience and green Brazil's economy. Brazil has the potential to overcome possible tradeoffs between energy use, emissions and growth. The new government's holistic approach to steer Brazil's ecological transformation and decarbonization

[32] The uncertainty of ETS prices has been shown to increase abatement costs by up to 15 percent (Fell, MacKenzie, and Pizer, 2021). An ETS without a price floor has a purely fixed emissions quantity, resulting in the impact of other mitigation policies being offset by lower ETS prices and, thus, ineffective.

[33] See Parry and others (2022) for more on design considerations.

and the BCB's drive to green and sustainable regulation and supervision reflect this potential well and provide promising avenues towards meeting the country's NDCs.

This paper discussed four main policy options to further enhance these initiatives. First, fiscal incentives and private sector crowding-in for forest protection would help boost the Amazon's resilience. Second, more adaptation investment in climate-smart agriculture, including through the expansion of insurance schemes, would reduce food loss and price volatility against the backdrop of increasing drought frequency. Third, filling power gaps from climate-related shocks and avoiding fossil fuel consumption in the short term would require investment in renewable energy infrastructure. Finally, building on Brazil's very green energy mix and world-wide leading biodiversity, low- or negative-emission growth opportunities include energy export or export-oriented manufacturing to seize growing demand for green goods and services.

Annex 1. Design Issues for Feebates to Promote Forest Carbon Storage

A nationwide feebate focused on promoting forest carbon storage would involve a system of fees and rebates applied to landowners according to the formula:

$$(1) \quad \tau_t^{CS} \cdot \left(CS_t^i - CS_{t,BASE}^i\right) = Y_t$$

Here CS_t^i is tons of carbon stored on the property for an individual landowner *i* at time *t*; $CS_{t,BASE}^i$ is a baseline level of carbon storage attributed to that landowner at time *t*; τ_t^{CS} is a payment per ton of stored carbon (see below); and Y_t is the landowners' total payment at time *t* (or subsidy if Y_t<0). Landowners therefore pay fees, or receive rebates, in a future year depending on whether stored carbon is lower or higher than the baseline level.

Baselines. Baseline carbon storage in different land parcels could be based on REDD+ inventories. This will likely lose revenue (as the policy itself causes storage to increase above the baseline). Any net fiscal loss is likely modest however, because the feebate price applies to the difference between carbon storage and baseline storage rather than total storage. Moreover, baselines can be updated over time in a way that: (i) promote revenue neutrality; and (ii) avoids perverse incentives for landowners to clear forests.[34]

Payment Formulas. Feebates could involve annual tax/subsidy, or 'rental', payments, rather than large upfront payments. The problem with one-off, upfront payments is that changes in land use may not be permanent (e.g., a reforested area may die back due to fires or disease), requiring complex, ex-post re-payment procedures to provide adequate incentives to maintain the land-use change. Annual payments could equal the carbon price times the interest rate. That is, the price per ton of stored carbon could be:

$$(2) \quad \tau_t^{CS} = r \cdot \alpha_t^{CO2} \cdot \beta$$

Where *r* is the real interest rate, α_t^{CO2} is the price per ton on CO_2 emissions, and β converts a price per ton of CO_2 into a price per ton of carbon—given there are 3.67 tons of CO_2 per ton of carbon, $\beta = 3/11$. For illustration, a \$50 per ton price on CO_2 translates into a feebate price (τ_t^{CS}) of \$0.7 per ton of stored carbon per year, with a 5 percent interest rate. Fees/rebates might be administered every two years (to coincide with the prospective updating of REDD+ inventories).

Setting the CO_2 price. Emissions prices should be aligned with emissions objectives for forestry. Evidence on the price responsiveness of forestry emissions[35] at the country level might be used to establish an initial price trajectory and subsequently adjusting based on the observed future response. Generally, phasing in prices gradually according to a pre-announced schedule is recommended to promote certainty and minimize disruption costs.

Exemptions. Timber harvested for wood products (e.g., furniture, houses) potentially warrants some exemption from fees because the carbon emissions (released at the end of the product life) will be delayed, perhaps by several decades or more. These exemptions might be integrated into existing tax regimes for wood processors.

[34] Parry (2020).

[35] See for example Roe at al. (2021).

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