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RESEARCH ARTICLE

Nature-based solutions are critical for putting Brazil on track towards net-zero emissions by 2050

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Abstract
Most of the world's nations (around 130) have committed to reaching net-zero carbon dioxide or greenhouse gas (GHG) emissions by 2050, yet robust policies rarely underpin these ambitions. To investigate whether existing and expected national policies will allow Brazil to meet its net-zero GHG emissions pledge by 2050, we applied a detailed regional integrated assessment modelling approach. This included quantifying the role of nature-based solutions, such as the protection and restoration of ecosystems, and engineered solutions, such as bioenergy with carbon capture and storage. Our results highlight ecosystem protection as the most critical cost-effective climate mitigation measure for Brazil, whereas relying heavily on costly and not-mature-yet engineered solutions will jeopardise Brazil's chances of achieving its net-zero pledge by mid-century. We show that the full implementation of Brazil's Forest Code (FC), a key policy for emission reduction in Brazil, would be enough for the country to achieve its short-term climate targets up to 2030. However, it would reduce the gap to net-zero GHG emissions by 38% by 2050. The FC, combined with zero legal deforestation and additional large-scale ecosystem restoration, would reduce this gap by 62% by mid-century, keeping Brazil on a clear path towards net-zero GHG emissions

by around 2040. While some level of deployment of negative emissions technologies will be needed for Brazil to achieve and sustain its net-zero pledge, we show that the more mitigation measures from the land-use sector, the less costly engineered solutions from the energy sector will be required. Our analysis underlines the urgent need for Brazil to go beyond existing policies to help fight climate emergency, to align its short- and long-term climate targets, and to build climate resilience while curbing biodiversity loss.

KEYWORDS
Brazil, climate change, deforestation, integrated assessment modelling, mitigation, nationally determined contribution, nature-based solutions, net-zero emissions

1 | INTRODUCTION

Our best chance to limit the average global temperature increase to 1.5°C above pre-industrial levels by the end of this century with no or limited overshoot is to almost halve greenhouse gas (GHG) emissions by 2030, reach net-zero carbon dioxide (CO_2) emissions globally by mid-century and maintain CO_2 removals thereafter (Fankhauser et al., 2022; IPCC, 2018; Riahi et al., 2022). The Paris Agreement provides an international framework for climate action aiming to keep the average global temperature increase to well below 2°C above pre-industrial levels and to pursue efforts to limit temperature rise to 1.5°C. As part of this global collective effort to reduce the most severe consequences of the climate crisis, signatory countries agreed to undertake and communicate increasingly ambitious efforts over time. The parties have submitted new or updated national climate pledges called nationally determined contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC) since 2020. However, pledges from the latest NDCs fall short of limiting warming to 1.5°C, with several countries even decreasing their ambitions relative to their first NDCs (Climate Action Tracker, 2021; UNEP, 2021a). Currently, more than one hundred countries have committed to net-zero CO_2 or net-zero GHG emissions pledges (Net Zero Tracker, n.d.) but less than half are in laws or policy documents pointing to a gap between promises and action (Van Soest et al., 2021). Moreover, many short-term NDC targets do not meet the ambition of mid-century net-zero goals (Black et al., 2021; Rogelj et al., 2021).

Brazil, among the most biodiverse countries on Earth, was one of the first developing countries to present economy-wide and absolute emissions reduction targets in its first NDC to the UNFCCC (Brazil, 2015). In contrast, the first update of its NDC in 2020 (Brazil, 2020a) violates the progression and non-regression principles of the Paris Agreement (UNEP, 2021a; Unterstell & Martins, 2022), among other issues (Table S1; Supporting Information). Brazil announced changes to its climate plan (Brazil, 2021a, 2021b) during the Glasgow Climate Change Conference (COP26), which were later confirmed in the second update of its NDC (hereafter referred to as 'Brazil's latest NDC') in 2022 (Brazil, 2022a). It includes a revision to the 2030 target and the anticipation in one decade of its long-term commitment to reaching net zero by mid-century. However, Brazil's latest climate plan is considered insufficient as its pledges, including net zero, need improvements and robustness to be consistent with the Paris Agreement's temperature goal (Climate Action Tracker, n.d.). It also fails to incorporate efforts aligned with the Glasgow Leader's Declaration on Forests and Land Use, and the Global Methane Pledge (Unterstell & Martins, 2022). While Brazil's latest NDC is ambiguous on net-zero CO_2 or net-zero GHG emissions, an official supporting letter submitted to the UNFCCC is clear on net-zero GHG emissions target (Brazil, 2021a).

Land-use change, which includes deforestation, is a major source of GHG emissions and the biggest driver of biodiversity loss on land, threatening health and resilience of ecosystems and the people dependent upon them (IPBES, 2019). While the land use, land-use change, and forestry (LULUCF), and agricultural sectors contribute to one-third of global gross GHG emissions (IPCC, 2019), they account for almost three-quarters in Brazil (SEEG, 2020). In 2020, the LULUCF sector alone was responsible for almost half (46%) of Brazil's gross GHG emissions, with nearly 90% caused by deforestation (SEEG, 2020). Brazil is one of the world's top GHG emitters (UNEP, 2021c) and has a historical responsibility with its emissions mainly coming from land use rather than burning fossil fuels (Evans, 2021). At present, only 12% of Brazil's original Atlantic Forest biome remains (SOS Mata Atlântica, 2022), almost half of the Cerrado is gone (Souza et al., 2020), and about one-fifth of the Brazilian Amazon has been deforested (Lovejoy & Nobre, 2019; PRODES, n.d.). Despite the sharp reduction of more than 80% in the Amazon's annual deforestation rates between 2004 and 2012, forest destruction has increased since then (PRODES, n.d.).

Currently, most of the deforestation in Brazil is illegal (Azevedo et al., 2022), happening in undesignated public lands, protected areas such as conservation units and indigenous territories, and private lands. Between 1985 and 2018, 78% of native vegetation losses in Brazil occurred in private properties and 19% in undesignated lands (Pacheco & Meyer, 2022). A study has shown that 90.5% of all areas claimed as farms in Brazil's Rural Environmental Cadastre (CAR), in southern Amazonas, are illegal (Carrero et al., 2022). From 2019 to 2021, almost 98% of the deforested areas in Brazil were directly or indirectly driven by agriculture

(Azevedo et al., 2022). To regulate land use and deforestation within farms, Brazil has its Native Vegetation Protection Law (No. 12,651/2012), also known as Brazil's Forest Code (FC) (Supporting Information). This legislation has the potential to prevent emissions from illegal deforestation and offset emissions through large-scale ecosystem restoration of illegally converted areas. Nevertheless, the FC is not a zero-deforestation law. The native vegetation that surpasses its threshold of protection can be deforested legally. Although this legislation dates back to 1965 and suffered a significant revision in 2012 (Brancalion et al., 2016; Soares-Filho et al., 2014), its practical implementation remains a major challenge (Chiavari et al., 2023; Igari et al., 2021). Considering Brazil's emissions profile, the full implementation of the FC is crucial for the country to reduce its emissions (Bustamante et al., 2019; Metzger et al., 2019; Soterroni et al., 2018).

According to the most recent IPCC Assessment Report (AR6), if we are to achieve net-zero CO_2 emissions globally by mid-century, carbon dioxide removal (CDR) will be unavoidable to counterbalance hard-to-abate residual emissions (IPCC, 2022). CDR refers to approaches that remove CO_2 from the atmosphere and store it on land, on geological formations, in oceans or in products (Smith et al., 2023). It is often described as a negative emissions technology and can be biological, chemical, land-based, conventional or novel (Smith et al., 2023). CDR methods include afforestation, ecosystem restoration, biochar, bioenergy with carbon capture and storage (BECCS), ocean fertilisation, and direct air carbon capture and storage (DACCS). BECCS is a class of technologies and practices that include both bioelectricity and bioliquids production with carbon capture and storage (CCS). The final result is the possibility of negative carbon emissions from an energy system (Köberle et al., 2020). Although afforestation and BECCS are biological CDRs, they are not nature-based solutions (NbS) and can have detrimental effects on species diversity. Afforestation with non-native monocultures in non-forest ecosystems could compromise water and food security (Seddon et al., 2020), and local livelihoods (Fleischman et al., 2020). A major concern with global integrated assessment modelling (IAM) approaches is their reliance on afforestation and BECCS as key strategies for achieving emissions reduction goals. IAMs are mathematical tools used to quantitatively describe key processes in the human and Earth systems. Their analytical framework combines elements from different disciplines, including engineering, economics, climate and land use (Keppo et al., 2021). Afforestation and BECCS will require significant land areas and water resources for biofuel production, which will intensify the competition for land, increase food prices and pose a threat to biodiversity (Seddon, 2022).

Conversely, NbS, which include the protection, restoration, and sustainable management of natural and semi-natural ecosystems, have the potential to make an essential contribution to reaching net-zero CO_2 globally by around 2050 (Girardin et al., 2021; Griscom et al., 2017; Roe et al., 2019), if implemented alongside a rapid and significant reduction of GHG emissions elsewhere (Seddon et al., 2020). Compared to engineered solutions such as CCS, NbS are often less costly and ready to be deployed at scale (Seddon, 2022). The global mitigation potential associated with NbS is roughly 10 gigatonnes of carbon dioxide ($GtCO_2$) per year, which corresponds to around 27% of current global annual emissions (Girardin et al., 2021). In countries with high forest cover and low fossil fuel emissions, such as Brazil, NbS are expected to be particularly critical in addressing climate change and biodiversity loss (Roe et al., 2021). If carefully implemented, NbS can provide multiple benefits for both human well-being and biodiversity, reduce the risk of impermanence, and increase social and ecological resilience to the impacts of climate change (Seddon, 2022; Seddon et al., 2020).

Previous research has projected low-emissions trajectories for Brazil, but these prior studies vary considerably in their scope (De Oliveira Silva et al., 2018; Dumas et al., 2022; Gurgel et al., 2019; Köberle et al., 2020; La Rovere et al., 2018; Rochedo et al., 2018; Roe et al., 2019, 2021; Schaeffer et al., 2020). While some confine their focus to specific mitigation measures or limited sectors and biomes (De Oliveira Silva et al., 2018; Dumas et al., 2022), others do not comprehensively assess specificities of national policies such as the FC across the interconnected sectors of LULUCF, agriculture and energy (Gurgel et al., 2019; Köberle et al., 2020; La Rovere et al., 2018; Rochedo et al., 2018; Schaeffer et al., 2020). Additionally, previous studies do not account for the substantial potential of NbS and engineered solutions in emissions reduction under detailed national policies (Roe et al., 2019, 2021), and do not distinguish between the impacts of illegal versus legal deforestation or solely rely on afforestation with non-native monocultures in climate change mitigation scenarios. Furthermore, no prior national modelling studies on Brazil's low-emissions pathways have taken into account the nation's commitment to achieving net-zero GHG emissions, as articulated in Brazil's latest NDC to the UNFCCC.

To address these limitations, we conducted an in-depth integrated analysis, spanning across all Brazilian sectors and biomes, including significant emissions-intensive sectors such as LULUCF, agriculture and energy. Our model is grounded in a baseline scenario validated against national statistics for the historical period, with deforestation rates and other land-use changes estimated endogenously rather than defined as exogenous constants. As such, our study pioneers a comprehensive quantification of the contribution of implementing existing and expected national policies, particularly from the LULUCF sector, towards achieving Brazil's net-zero pledge. To this end, we employ a unique regional IAM approach that synergistically combines two well-established and intricate models specially tailored for the Brazilian context. These models are the regional version of the Global Biosphere Management model for Brazil (GLOBIOM-Brazil) (Soterroni et al., 2018, 2019), known for its capacity to simulate regional economic partial equilibrium and land use dynamics, and the process-based integrated assessment, Brazilian Land-Use and Energy Systems model (BLUES) (Rochedo et al., 2018). By employing this innovative modelling strategy, we project Brazil's GHG emissions across all sectors of the economy up to 2050, under policy scenarios that are nationally meaningful and aligned with net-zero

TABLE 1 Short description of our policy scenarios.

Scenario name	Short description	Net-zero GHG target by 2050	Additional mitigation measures relative to BASE starting from 2020 onwards
Baseline (BASE)	This scenario represents weak environmental governance, where deforestation continues throughout Brazil up to 2050, with Amazon deforestation rates above 1 Mha, on average, between 2020 and 2030. There is no native vegetation restoration, and agricultural practices follow current trends, including pasture recovery and afforestation, in line with the New Low-Carbon Agriculture Plan (ABC+ Plan). The energy sector considers agreed and installed infrastructure and energy policies currently in place	No	-
Forest Code (FC)	Built upon the BASE, this scenario examines the contribution of a key land-use policy, Brazil's Forest Code, in decreasing the country's GHG emissions. Native vegetation restoration takes place in illegally deforested areas identified as environmental debts by the Rural Environmental Cadastre (CAR) dataset, excluding environmental debts in small farms	No	Zero illegal deforestation; native vegetation restoration (~13 Mha)
Forest Code Plus (FC+)	Built upon FC, this scenario goes beyond the Forest Code by eliminating both illegal and legal deforestation while promoting more than a twofold increase in the native vegetation restoration target relative to the FC. Restoration takes place in areas illegally deforested and identified as environmental debts by CAR, as well as in small farms that have been granted amnesty	No	Zero illegal and legal deforestation; native vegetation restoration (~35 Mha)
Baseline Net Zero (BASENZ)	Built upon BASE, this scenario allows the energy sector to go beyond existing and agreed infrastructure to bridge the gap to a least-cost net-zero GHG	Yes	Increase in efficiency, biofuels use, and deployment of negative emissions technologies (such as BECCS) from the energy sector
Forest Code Net Zero (FCNZ)	Built upon FC, this scenario allows the energy sector to go beyond existing and agreed infrastructure to bridge the gap to a least-cost net-zero GHG	Yes	Zero illegal deforestation; native vegetation restoration (~13 Mha); increase in efficiency, biofuels use, and deployment of negative emissions technologies (such as BECCS) from the energy sector
Forest Code Plus Net Zero (FC+NZ)	Built upon FC+, this scenario allows the energy sector to go beyond existing and agreed infrastructure to bridge the gap to a least-cost net-zero GHG	Yes	Zero illegal and legal deforestation; native vegetation restoration (approx. 35 Mha); increase in efficiency, biofuels use, and deployment of negative emissions technologies (such as BECCS) from the energy sector.

Abbreviations: BECCS, bioenergy with carbon capture and storage; GHG, greenhouse gas; Mha, million hectares.

ambition (as outlined in Table 1). Our analysis quantifies the gap to net zero by mid-century under the lens of our policy scenarios, underscoring the discrepancy between Brazil's net-zero pledge and its prevailing environmental and climate policies. Additionally, our study accounts for the trade-offs between sectors and quantifies the potential emissions reductions resulting from key activities, including nature-based and engineered solutions, and estimates the relative economic efforts undertaken within the energy and land-use sector in our net-zero pathways.

2 | METHODS

The GLOBIOM-Brazil model projects emissions from the LULUCF and agricultural sectors, while the BLUES model projects emissions from the energy, industrial processes (IP) and waste sectors. Both models are regional versions of global models for Brazil with better input data, resolution, calibration and validation against national statistics. Regional models capture local specificities in greater detail than global models, enabling the construction of realistic national policy scenarios. In our soft-link approach, the outputs of one model are inputs to the other model, which run separately. The following is a brief description of each model, emissions estimates, cost calculations and scenarios used in this study.

2.1 | Land use modelling (GLOBIOM-Brazil model)

GLOBIOM-Brazil (Soterroni et al., 2018, 2019) is based on the global bottom-up, partial equilibrium, land-use model GLOBIOM, which is described in previous studies (Havlík et al., 2011, 2014) and in the model's documentation with full equations (Havlik & Frank, n.d.; IBF-IIASA, 2023). Both models simulate the competition for land among agricultural, forestry and bioenergy sectors subjected to resources, technology and policy restrictions. Land-use changes, which include native vegetation losses (hereafter also referred to as 'deforestation'), are not imposed on the model as exogenous demands. Conversely, they are endogenously estimated based on market signals combined with land suitability, biophysical information, production and land conversion costs, and scenarios constraints. As GLOBIOM, GLOBIOM-Brazil represents more than 30 commodities, including 18 crops (such as soybeans, maize and sugarcane), meat and milk for five animal types (cattle, sheep, goat, pigs and poultry), biofuels (such as sugarcane ethanol), and wood products (such as sawnwood and pulpwood). Mathematically, the competition for land is simulated at the pixel level by maximising the welfare (i.e. the sum of consumer and producer surpluses). The production is endogenously adjusted to meet the demands for food, feed, fibres and bioenergy of 30 different regions, including Brazil, interconnected through international trade. The prior demands for each region and product are driven by exogenous factors such as gross domestic product (GDP), population growth and dietary trends, which are derived from the Shared Socioeconomic Pathways (SSPs) (Fricko et al., 2017). The exogenous biofuels demand is based on the 2010 World Energy Outlook projections (International Energy Agency, 2010), and the demand for sugarcane ethanol in Brazil comes from the Energy Research Enterprise (EPE) projections of the Ministry of Mines and Energy (MME) (EPE, 2017). The model is recursively dynamic and runs with 5- or 10-year time steps, starting at the baseline year of 2000 and up to 2100. Here, we ran GLOBIOM-Brazil with 5-year time steps, which gives more flexibility in defining cut-off dates of local policies and national commitments. The model uses a geographical grid of 0.5°×0.5° within Brazil (approximately 50 km×50 km at the Equator) and 2°×2° outside Brazil (approximately 200 km×200 km at the Equator). GLOBIOM-Brazil optimises, at the pixel level, over six land use classes, including unmanaged native vegetation, pastures, croplands and non-productive lands (Table S2). A land use class for ecosystem or native vegetation restoration in Brazil (hereafter referred to as 'native vegetation restoration' or simply 'restoration') is also available in GLOBIOM-Brazil (Soterroni et al., 2018). The possible land-use conversions and land conversion costs are defined by a matrix of endogenous land-use change (Soterroni et al., 2018). GLOBIOM-Brazil estimates emissions from agriculture and LULUCF sectors. More details of the GLOBIOM-Brazil model are available in the Supporting Information.

2.2 | Process-based, integrated assessment energy and land-use systems modelling (BLUES model)

BLUES (Rochedo et al., 2018) is a least-cost optimisation model for Brazil, built on the MESSAGE model generation platform (Model for Energy Supply Strategy Alternatives and their General Environmental Impact). BLUES has six regions, one representing national processes in which five sub-regions are nested, following Brazil's geopolitical division. BLUES optimises the energy system between 2010 and 2060 in 5-year intervals, minimising the system's total cost and having perfect foresight of future technical, economic and political conditions. Each representative year is divided into 12 representative days (one for each month) made up of 24 representative hours, resulting in 288 time slices. Power generation must balance supply for each time slice. The energy system is detailed across the energy transformation, transportation and consumption sectors, with over 1500 technologies customised for each of the six native regions. The costs and performance characteristics (such as efficiencies, capacity factors and environmental indicators) of technological alternatives are among the most important inputs to the model. These values can change over the model time scale (e.g. representing cost reduction and improving technology efficiency). Primary energy sources undergo a transformation process until they become energy services to supply demand. Energy demands are exogenously calculated from the SSP2 pathway (Fricko et al., 2017), using elements such as future GDP and population growth. They can be divided regionally and, in certain cases as for electricity, it is possible to represent a system load curve. The total cost of the energy system includes investment costs, operational costs and additional costs such as "penalties" for specific alternatives or environmental and social costs. The model minimises the costs of the entire energy system, including the electricity generation, agriculture, industry, transport, waste and building sectors, subject to constraints that represent real-world restrictions. Although BLUES represents the agricultural and the land-use sectors (Köberle, 2018), in this study these sectors come from the GLOBIOM-Brazil model. The BLUES land use and agricultural sectors were only used in the convergence process to ensure the robustness of the results. The BLUES model is based on the MESSAGE platform, which has been described, with full equations, in previous publications (IAEA, 2007; Nogueira De Oliveira et al., 2016; Strubegger et al., 2004).

2.3 | Convergence process between GLOBIOM-Brazil and BLUES models

Since Brazil's decarbonisation would encompass an increase in biomass feedstock demand, and this production requires land to grow, GLOBIOM-Brazil must appropriately account for the area required by the biofuels demand in BLUES. Thus, the additional areas dedicated to energy crops and tree plantations projected by BLUES under net-zero pathways are incorporated into the GLOBIOM-Brazil model via exogenous biofuels demands. The spatially explicit location of these additional areas results from the competition for land and the biophysical parameters from GLOBIOM-Brazil. Our convergence process accepts a difference within 15% between the areas projected by BLUES and GLOBIOM-Brazil models. Hence, in this study, the LULUCF and agricultural sectors from BLUES were only used to quantify the additional areas needed for biofuels production.

2.4 | Emissions calculations (LULUCF and agricultural sectors)

GLOBIOM-Brazil estimates emissions from the LULUCF and agricultural sectors. The model accounts for CO_2 emissions and removals due to land-use changes, and non-CO_2 emissions such as nitrous oxide (N_2O) from fertiliser use, methane (CH_4) from rice cultivation and enteric fermentation, and CH_4 and N_2O from manure management (Table S3). Non-CO_2 emissions are expressed as carbon dioxide equivalent (CO_2e) using GWP_{100} in AR5 and are based on IPCC accounting guidelines. We also consider emissions reduction from recovery of degraded pastures (Cohn et al., 2014) by 1 tC/ha/year (Observatório ABC, 2015). CO_2 emissions or removals from the LULUCF sector result from the difference in the carbon content (above- and below-ground biomass) between the original and the new classes. Deforestation causes CO_2 emissions (positive emissions). Native vegetation restoration and afforestation with non-native monocultures in short-rotation plantations, such as eucalyptus and pinus, sequester CO_2 (negative emissions). Given our detailed representation of the LULUCF sector, we can distinguish between carbon sequestration through afforestation and restoration, which are usually not differentiated by several studies. In GLOBIOM-Brazil, the CO_2 release from the terrestrial biosphere to the atmosphere occurs in one simulation period. CO_2 sequestration from afforestation considers the rotation period of such plantations, while CO_2 sequestration from restoration could take years to several decades, depending on the type of vegetation being restored. In the Amazon and Atlantic Forest biomes, forest restoration takes 25 years to recover 70% of the original biomass (Ramankutty et al., 2007). For the other biomes, we follow the methodology from Soterroni et al. (2018), where the full recovery of biomass contents in the Cerrado, Caatinga and Pantanal biomes is assumed to take 20 years (70% in the first decade and 30% in the second). The grassland-based vegetation of the Pampa biome is assumed to regenerate in 5 years (or one time step). Carbon stock information comes from different biomass maps (Table S3), including national sources such as the above- and below-ground biomass from the Third Brazil's Emissions Inventory (Brazil, 2016). Our estimates do not consider dead wood, litter and soil organic carbon.

2.5 | Emissions calculations (carbon removals by native forests)

GLOBIOM-Brazil does not account for carbon sequestration from secondary vegetation growth and undisturbed native forests in protected areas. To estimate this contribution, we rely on Brazil's latest national communications (NCs) to the UNFCCC, despite high levels of uncertainty in those estimates. According to IPCC guidelines (IPCC, 2006), countries are allowed to include CO_2 removals from managed forests in their national emissions inventories. In Brazil, forests within conservation units and indigenous lands are classified as managed forests due to ongoing human interventions necessary to protect those areas. Brazil's fourth National Communication to the UNFCCC (4th NC) (Brazil, 2020b) reports that the annual average CO_2 removals derived from the CO_2 removal matrices amounts to 610 million tonnes of carbon dioxide ($MtCO_2$) for the period 2002–2010, and 522 $MtCO_2$ for the period 2010–2016 (Brazil, 2020c). The independent GHG emission and removal estimating system (SEEG) estimates carbon removals to be quite flat, averaging 620 $MtCO_2$/year between 2014 and 2020 (SEEG, 2020). SEEG is an independent initiative developed by the Climate Observatory that generates annual estimates of Brazilian GHG emissions from 1970 to the present across key economic sectors. It follows the IPCC guidelines and is based on national inventories and country specific data, encompassing emissions factors, processes, raw data from various official and non-official sources, and social and economic indicators (Azevedo et al., 2018). The significant differences in official statistics and NCs to the UNFCCC (Table S4) illustrate the high uncertainty on carbon removals from native vegetation in Brazil. In this study, we use a conservative assumption of a fixed carbon removal by native forests per year, from 2015 to 2050, following Brazil's 4th NC average estimates for 2010–2016 (i.e. 522 $MtCO_2$ per year).

2.6 | Emissions calculations (energy, IP and waste sectors)

Emissions from the energy, waste and IP sectors are projected by BLUES (Rochedo et al., 2018). The model calculates CO_2, CH_4 and N_2O emissions individually, as well as total GHG emissions, using GWP_{100} in AR5 to express it as CO_2e. Energy emissions cover production and transformation of the energy carriers and emissions derived from fossil fuels combustion at the end-use sectors. Energy production includes various activities such as the exploration and production of oil and gas, coal mining, electricity production, refining of oil products, and distilleries. The model also accounts for fugitive emissions, process emissions in the production of hydrogen and the sequestration of CO_2 when CCS technologies are applied to energy production. This may lead to a reduction of CO_2 emissions when applied to fossil fuels consumption, such as natural gas and coal power plants, or to negative emissions when associated with BECCS, such as in the case of ethanol production and biomass to liquids plants. The end-use sectors of energy emissions include passenger and freight transportation, as well as 11 industry sub-sectors (cement, ceramics, chemicals, food and beverage, iron and steel, metallurgy, mining, alloys, paper and pulp, textile, and other sectors), household and commercial/services. Waste emissions cover the treatment of urban solid waste, health solid waste, and effluent residues. It accounts for dumping grounds, landfills, composting, biodigestion, incineration and recycling emissions. Industrial process emissions refer to emissions not related to fossil fuel combustion but from the chemical reactions derived from chemical products fabrication, for instance. Most come from chemical, cement, and iron and steel subsectors.

2.7 | Scenarios description

The policy and net-zero scenarios in this study (Table 1) are built upon a baseline trajectory (BASE). Here, our BASE uses the "middle of the road" SSP2, which implies a future with moderate challenges to mitigation and adaptation, regardless of the scenario. The SSP2 projects a 28% growth in population and a 174% growth in GDP for Brazil between 2000 and 2030. For comparison purposes, according to the Brazilian Institute of Geography and Statistics (IBGE), Brazil's population is expected to increase by 29% by 2030. Furthermore, our BASE scenario is validated against national statistics for the historical period (Supporting Information). All scenarios are identical up to 2020 but assume different trajectories from 2021 to 2050. Regarding the LULUCF and agricultural sectors, both BASE and the FC scenarios are based on the *IDCImperfect2* and the *FC* scenarios, respectively, from Soterroni et al. (2018) (Supporting Information).

Our BASE tries to capture a weak environmental governance in Brazil through an imperfect illegal deforestation control and no restoration during the simulation period (Soterroni et al., 2018). Regarding deforestation, the BASE scenario is validated against PRODES for the historical period (Table S5; Supporting Information). Our FC scenario attempts to capture the full implementation of key dispositions in Brazil's FC, including zero illegal deforestation, restoration of illegally deforested areas (also called environmental debts), environmental reserve quotas (CRA), and the amnesty for illegally converted areas in small farms. CRAs are an offset mechanism where environmental debts in one property can be compensated by conserving surpluses of native vegetation in another property (Soares-Filho et al., 2016). The final restoration target (~13 Mha) is determined by the total environmental debts of Legal Reserves and Areas of Permanent Preservation, which is derived from the CAR (Guidotti et al., 2017), with part of the Legal Reserve debts compensated by the CRA mechanism (Soterroni et al., 2018). The final environmental debt area is set aside for restoration within the model, following the geometric progression of the National Plan for Restoration of Native Vegetation (PLANAVEG) schedule (Brazil, 2017). Once created, no further land-use changes are allowed within these areas. Our FC+ scenario is built upon the FC but eliminates both illegal and legal deforestation while promoting the restoration of ~35 million hectares (Mha) of native vegetation from 2021 onwards. The restoration target of the FC+ is the sum of the restoration target of the FC scenario and the amount of illegally deforested areas within small farms that were granted amnesty during the 2012 revision of the FC (Guidotti et al., 2017). Restoration under the FC+ follows the PLANAVEG schedule (geometric progression) from 2020 to 2035. After 2035, the restoration curve is allowed to increase linearly until the target is achieved. This linear increase is based on the latest yearly increment as designed by the PLANAVEG schedule. Agricultural practices follow the current trends regardless of the scenario, which includes the recovery of degraded pasture via semi-intensive cattle ranching production system (Cohn et al., 2014) and the expansion of double cropping soy-maize (Soterroni et al., 2019). All scenarios account for afforestation and recovery of degraded pastures, which are expected to contribute to almost 60% of the total mitigation potential under the new Low-Carbon Agriculture Plan (ABC+ Plan) (EMBRAPA, 2017; Rede ILPF, 2021). The LULUCF and agricultural assumptions for the net-zero scenarios BASENZ, FCNZ and FC+NZ follow the same assumptions from BASE, FC and FC+ scenarios, respectively. Ex-post analysis estimates the costs related to native vegetation restoration in the net-zero scenarios.

The assumptions regarding the energy, IP and waste sectors are the same for the BASE, FC and FC+ scenarios. They include current energy policies, such as the current and contracted installed capacities for electric generation sources, refineries, distilleries, transmission and distribution assets of the power sector. Specifically, the assumptions for BASE, FC and FC+ scenarios include: (i) the completion of the Angra 3 nuclear plant between 2025 and 2030; (ii) continuity of operation of the Jorge Lacerda coal-fired thermal power plant until 2040; (iii) the expansion of natural-gas-fired power plants; and (iv) the implementation of mandatory blending of biodiesel to all diesel fuel sold in the country at 20% (volumetric basis, B20) from 2028 onwards. These scenarios also account for international policies in place, such as the decarbonisation goals of the International Maritime Organization (IMO) and the International Air Transport Association (IATA), with emission reduction targets of 50% in 2050, relative to 2008 and 2005 emissions, respectively. The BASE, FC, and FC+ scenarios do not consider carbon capture technologies. Since there is no emission target, the model chooses only the tendential technologies. Conversely, for the net-zero scenarios (BASENZ, FCNZ and FC+NZ), the coal-fired and natural gas power plants, as well as the B20 biodiesel mandatory blend from the previous scenarios are not forced into the model. Instead, it can use all technological options, including CCS and BECCS, to reduce emissions and bridge the gap to net-zero GHG emissions in Brazil.

2.8 | Economic costs calculation

The needed economic efforts from the land use (LULUCF and agriculture) and energy sectors to achieve net zero are determined by relative costs to the BASE scenario. Costs from the land-use sector combine restoration implementation costs (Brancalion et al., 2019) and opportunity costs based on GLOBIOM-Brazil outputs and prices of commodities (CEPEA-Esalq/USP, n.d.). The BLUES model estimates the costs from the energy sector, including additional investments in energy efficiency, innovative technologies and negative emissions options such as BECCS. To standardise prices among our models and external information, we use US$$_{2019}$ currency (US$1.00 = R$4.03) based on the General Price Index—Internal Availability from Fundação Getúlio Vargas for December 2019. We use annualised costs over 2020–2050 by considering a 5% discount rate per year. As the standard currency in BLUES is US$$_{2010}$, we used the Chemical Engineering Plant Cost Index (CEPCI) as a dollar inflationary factor (CEPCI, 2019) to have all costs in US$$_{2019}$ currency.

Agricultural opportunity costs for implementing net-zero pathways are based on the reduction in agricultural production relative to the BASE scenario multiplied by Brazil's major commodity prices (soybeans, maize, sugarcane and beef). Production decrease is a result of land being set aside for restoration and protection through deforestation control measures. We consider an average price for each commodity based on annual prices from CEPEA/USP (CEPEA-Esalq/USP, n.d.), between 2017 and 2022, adjusted by GLOBIOM-Brazil changes in prices under net-zero scenarios relative to BASE. Total restoration costs are calculated by multiplying average restoration costs (US$ per hectare) and projected native vegetation restoration area (hectare). Average restoration costs are given per technique (total planting, enrichment planting, assisted natural regeneration, and natural regeneration) and biome (Table S6) following the estimates from Brancalion et al. (2019). Final restoration costs are weighted by PLANAVEG scenarios (high, moderate, low and very low) per biome (Table S7). Restoration area is given by the increment in native vegetation restoration as projected by GLOBIOM-Brazil model for the FCNZ and FC+NZ scenarios from 2021 to 2050 (Tables S8 and S9).

The BLUES model calculates the total cost of the energy and land use systems. Since GLOBIOM-Brazil simulates the LULUCF and agricultural sectors, we have neglected BLUES cost for the land use systems, focusing only on the energy costs. BLUES considers capital expenditures (CAPEX) and operational and maintenance (O&M) costs for all technologies in the model. Costs include exploitation of energy resources, construction of power utilities, electricity transmission and distribution, installation of refinery facilities, fuels and biofuels production, and transport of energy carriers. It also includes technologies at the end-use sectors, such as household appliances, vehicles in the passenger and transport sectors, costs of different waste treatment technologies, and IP. Early-stage technology costs decrease over time according to the learning curve of each option.

2.9 | Mitigation potentials

We estimate the mitigation potential of a given measure as the absolute difference in GHG emissions of this activity under a net-zero pathway relative to our BASE scenario. Mitigation potentials from the LULUCF sector are broken down into protection (through avoiding deforestation), restoration (of native vegetation) and afforestation (with non-native monocultures). The mitigation potential of the agricultural sector accounts for emissions reduction from degraded pasture recovery and a decrease in production due to trade-offs with land-use policies. The mitigation potentials of the energy sector are divided into BECCS and reduced emissions due to greater use of renewables and efficiency increase.

3 | RESULTS

3.1 | Baseline

After a decrease in projected emissions between 2015 and 2020, future net GHG emissions in Brazil, under the BASE scenario, are expected to increase and remain relatively stable from 2025 onwards (Figure 1). Under this scenario, emissions increase from the agricultural and energy sectors are balanced by emissions reduction from the LULUCF sector (Figure S1). Although emissions from the LULUCF sector will decrease compared to 2020 levels, native vegetation losses will continue up to 2050 (Figure S2). During this decade (2020–2030), deforestation in Brazil will reach 2.91 Mha per year, on average, under the BASE scenario with 37% (or around 1.08 Mha per year) projected to take place in the Amazon biome, a similar figure of recent years (PRODES, n.d.). Between 2030 and 2050, accumulated deforestation in the Amazon and Cerrado biomes is estimated to reach 26 Mha, which exceeds the size of the United Kingdom (Table S5). Built upon the BASE, the FC and FC+ scenarios evaluate the role of existing and expected policies mainly connected to zero deforestation and large-scale restoration towards Brazil's net-zero pledge. The impacts of these scenarios on land-use changes and major agricultural commodities can be seen in Figures S2–S5.

3.2 | Policy gap

Brazil's gap to net-zero GHG emissions by 2050 would be 1,481 million tonnes of carbon dioxide equivalent ($MtCO_2e$), according to the BASE scenario (Figure 1; Table S10). Full implementation of the FC (FC scenario) bridges 38% of the gap to net-zero GHG emissions by mid-century, decreasing overall emissions from 1,481 to 918 $MtCO_2e$ (Figure 1; Table S11). The FC+ scenario, which further eliminates legal deforestation and has a restoration area 2.7 times larger than the area projected by the FC scenario, would reduce this gap by 62%, amounting to 561 $MtCO_2e$ of net emissions by 2050 (Figure 1; Table S12). If we consider a linear path towards net-zero GHG emissions between 2015 and 2050, Brazil would be below or close to this path up to 2030 under the FC scenario, and up to 2040 under the FC+ scenario. While not enough to fully bridge the gap to net-zero GHG emissions by mid-century, both the FC and FC+ scenarios would enable Brazil to achieve its short-term NDC targets as outlined in the latest (indicated by blue marks in Figure 1) or the first NDC (indicated by purple marks in Figure 1). This points to a policy

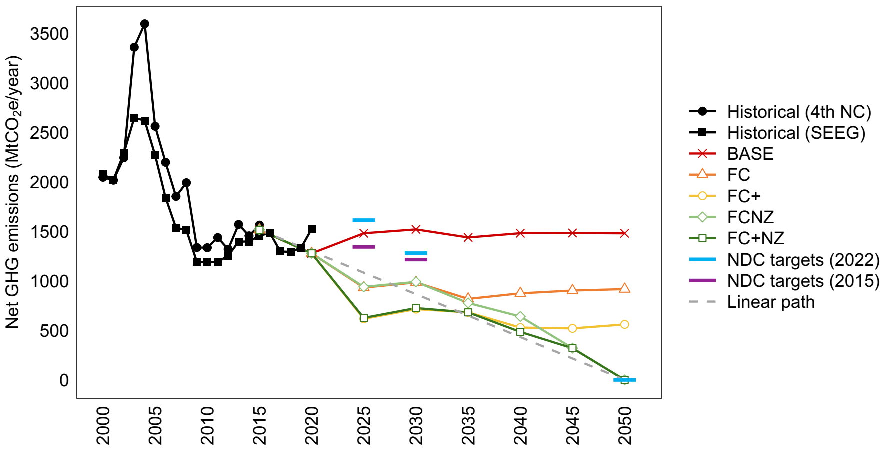

FIGURE 1 Brazil's future net greenhouse gas (GHG) emissions for all sectors. Brazil's net GHG emissions trajectories (2015–2050) as projected by the various scenarios. Yearly historical emissions are from Brazil's fourth National Communication to the United Nations Framework Convention on Climate Change (UNFCCC) (4th NC) up to 2015 (Brazil, 2020b) and the GHG emission and removal estimating system (SEEG) initiative up to 2020 (SEEG, 2020). The latest nationally determined contribution (NDC) short-term targets (37% and 50% emissions reduction by 2025 and 2030, respectively, relative to 2005 levels) and long-term pledge (net-zero GHG emissions by 2050) (Brazil, 2022a) are represented by blue marks. First NDC's absolute targets for emissions reductions for 2025 and 2030 are represented by purple marks (Brazil, 2015). A linear path toward net zero starts in 2015. Values are in million tonnes of carbon dioxide equivalent ($MtCO_2e$) using GWP_{100} from IPCC AR5. BASE, baseline scenario; FC, Forest Code scenario; FC+, Forest Code Plus scenario; FCNZ, Forest Code Net Zero scenario; FC+NZ, Forest Code Plus Net Zero.

gap between Brazil's long-term net-zero pledge and the country's current and expected environmental and climate policies.

3.3 | Short- and long-term targets

By construction, the gap to net-zero GHG emissions left by the BASE, FC and FC+ scenarios could be bridged by the energy sector in our net-zero pathways. The portfolio of options in BLUES includes diverse technologies that could reduce emissions at various technological readiness levels. They range from already established technologies such as wind power plants to mid-stage deployment options such as electric vehicles and energy storage. They also account for early-stage research technologies such as BECCS and DACCS. However, our modelling approach suggests that achieving net-zero GHG emissions under the baseline scenario (BASENZ) is not feasible. The available engineered solutions will not be able to compensate for future emissions in Brazil if deforestation rates and agricultural practices continue following current trends. Due to this infeasibility, our modelling framework does not provide outputs for this scenario. Hence, the BASENZ scenario does not appear in Figure 1. It is worth noting that Brazil's short-term 2025 NDC target (indicated by the blue mark in Figure 1) is expected to be achieved even under the BASE scenario. By 2030, the country will not reach its NDC goal (indicated by the blue mark in Figure 1) by 239 $MtCO_2e$ under the same trajectory. This would represent only 11% of Brazil's gross emissions projected for that year. In short, the BASE scenario that might fulfil the latest NDC short-term commitments is incompatible with Brazil's long-term net-zero pledge, reinforcing the need to revise and better align short- and long-term targets.

3.4 | Mitigation potential of key activities

We assessed the mitigation potential of key activities and sectors as projected by the net-zero scenarios FCNZ and FC+NZ relative to the BASE for the period 2020–2050 (Tables S13 and S14). We found that protection has the highest contribution among all considered measures, providing from 51% (FCNZ) to 60% (FC+NZ) of the necessary CO_2e mitigation for Brazil to achieve its net-zero pledge (Figure 2a,b). Compared to BASE, protection through deforestation control could prevent the release of 13,381 $MtCO_2e$ according to the FCNZ scenario and 18,094 $MtCO_2e$ as projected by the FC+NZ scenario during this period (Table S15). Moreover, protection plays a more significant role than any other mitigation measure per year, particularly in reducing Brazil's emissions in the near term. It contributes to over 90% of the overall emissions reduction between 2020 and 2030 (Figure 2c,d). Zero illegal deforestation (FCNZ scenario) has the potential to mitigate 446 $MtCO_2e$/year, on average, between 2020 and 2050, while preventing both illegal and legal deforestation (FC+NZ scenario) would mitigate 603 $MtCO_2e$/year, on average, during the same period.

Here we distinguish between carbon uptake from afforestation in short-rotation plantations and native vegetation restoration. Between 2020 and 2050, the mitigation potential of restoration varies from 10% (FCNZ) to 18% (FC+NZ), amounting to 2,523 $MtCO_2e$ and 5,331 $MtCO_2e$, respectively, of carbon uptake (Figure 2a,b; Table S15). Carbon storage can take years to decades to be accumulated by ecosystems and, based on our scenarios, the restoration target is not fulfilled in one time step, as it primarily follows the schedule outlined in PLANAVEG. Although restoration would provide a limited mitigation potential in the first decade (2020–2030), it

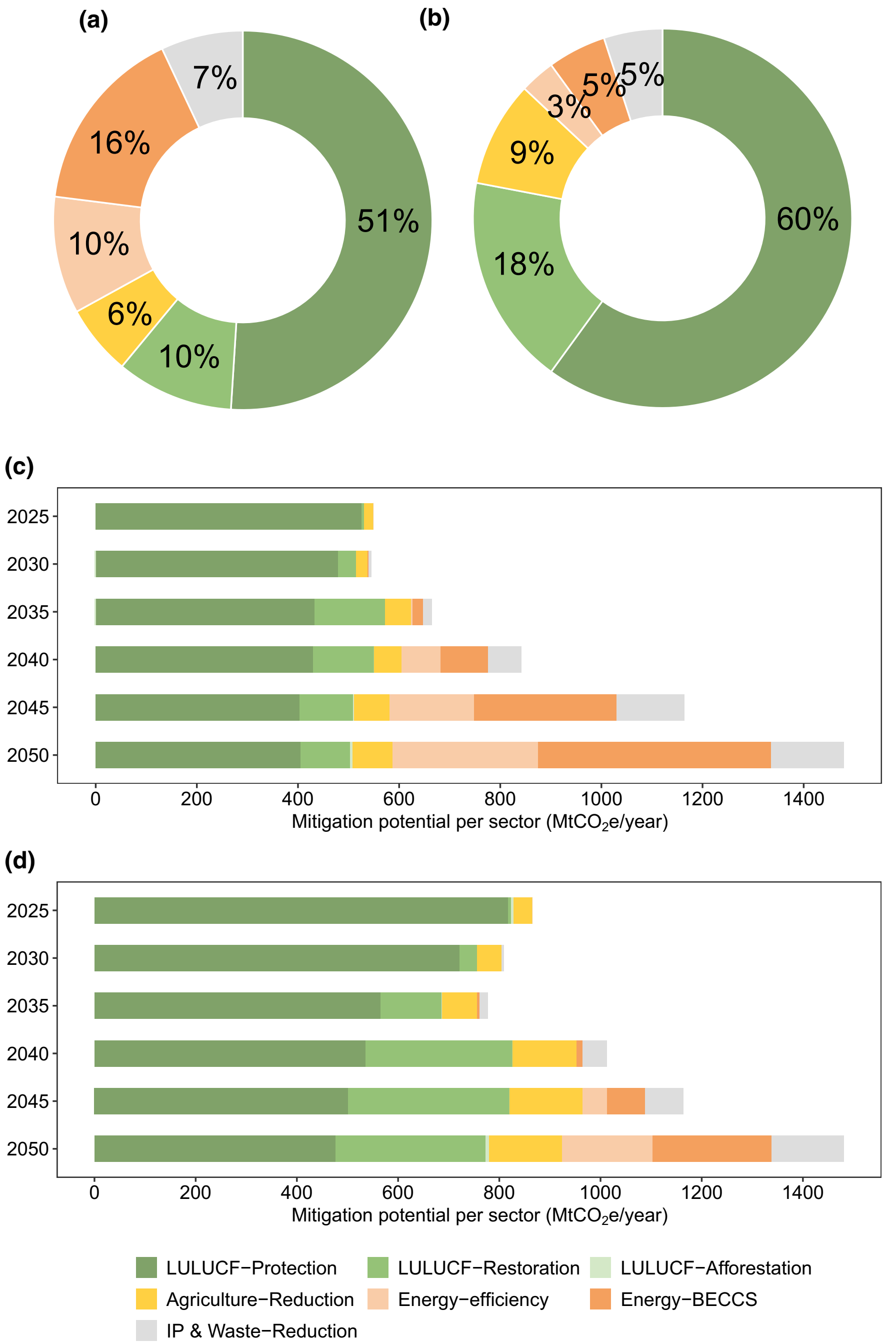

FIGURE 2 Mitigation potentials per sector and key activities. Accumulated mitigation potentials over 2020–2050 for the scenarios (a) FCNZ and (b) FC+NZ relative to the BASE scenario. Mitigation potentials evolution per year relative to the BASE scenario for different sectors and key activities as projected by the scenarios (c) FCNZ and (d) FC+NZ. Values are in million tonnes of carbon dioxide equivalent ($MtCO_2e$) using GWP_{100} and IPCC AR5. BECCS, bioenergy with carbon capture and storage; FCNZ, Forest Code Net Zero scenario; FC+NZ, Forest Code Plus Net Zero; IP, industrial processes; LULUCF, land use, land-use change, and forestry.

offers up to 139 $MtCO_2e$ of carbon uptake under the FCNZ scenario (Figure 2c) by 2035, and up to 319 $MtCO_2e$ by 2040, according to the FC+NZ scenario (Figure 2d). Moreover, well-designed ecosystem restoration goes beyond carbon and includes biodiversity conservation, provision of ecosystem services, and improvement of local livelihoods (Di Sacco et al., 2021; Hua et al., 2022).

Under the BASE scenario, afforestation would cover an area of 16 Mha in Brazil by 2050, contributing to a net removal of 1,725 $MtCO_2e$ between 2020 and 2050 (Table S15). Under FCNZ and FC+NZ scenarios, afforestation also follows BASE trends, which makes its contribution, in terms of emissions reduction, small relative to BASE (Figure 2c,d). When considering the accumulated mitigation potentials between 2020 and 2050, the contribution of afforestation relative to BASE is basically zero and it is omitted from Figure 2a,b. The need for BECCS under net-zero trajectories increases the demand for biomass feedstock, which mainly affects the area of afforestation (Figure S3f). The carbon sequestration of the new afforestation areas for BECCS is accounted as the BECCS contribution to emissions reductions.

Protection and restoration, as defined in our policy scenarios, directly impact agricultural production and the competition for land (Supporting Information). Even though agricultural intensification is performed by the model, including livestock intensification and expansion of double cropping for soy and maize, cattle herd and soybean production are expected to reduce compared to the BASE scenario (Figure S4). Thus, between 2020 and 2050, the agricultural

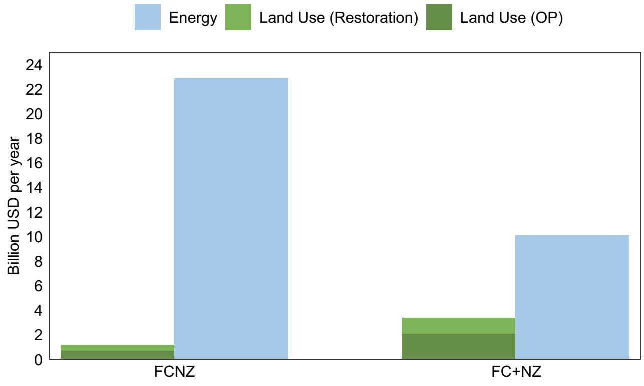

FIGURE 3 Relative costs under scenarios that bridge the gap to net zero. Relative costs in billion USD per year during 2020–2050 as projected by the FCNZ and FC+NZ scenarios. Costs from the land-use sector consider opportunity costs (OP) and restoration implementation costs. Costs from the energy sector consider the increase in energy efficiency and deployment of negative emissions technologies such as bioenergy with carbon capture and storage. We are using an annual discount rate of 5% over 2020–2050 and US$$_{2019}$ currency. FCNZ, Forest Code Net Zero scenario; FC+NZ, Forest Code Plus Net Zero.

sector would mitigate from 6% to 9% of the CO_2e needed to achieve net-zero emissions by mid-century under the FCNZ and FC+NZ scenarios, respectively, relative to the BASE (Figure 2a,b). It amounts to 1,480 $MtCO_2e$ under the FCNZ and 2,856 $MtCO_2e$ under the FC+NZ during the same period (Table S15).

Under our scenarios, efforts needed from the energy, IP and waste sectors will depend on the amount of emissions reduction and enhanced carbon sequestration from the LULUCF sector. Between 2020 and 2050, the total mitigation potential from energy, IP and waste sectors together amounts to 33% under the FCNZ scenario (Figure 2a), decreasing to 13% under the FC+NZ (Figure 2b). It would require a reduction in emissions of 8,695 $MtCO_2e$ under the FCNZ, and 3,905 $MtCO_2e$ under the FC+NZ during the same period to bridge the gap to net-zero GHG emissions (Table S15). Note that the mitigation potential of the energy sector is unevenly distributed over time (Figure 2c,d; Figure S6). It starts small and increases as we approach the net-zero target date for Brazil. By 2050, the CO_2e mitigation needed from the energy sector alone accounts for 51% (749 $MtCO_2e$) under the FCNZ scenario and 28% (414 $MtCO_2e$) under the FC+NZ, with most of those contributions coming from BECCS (Figure S7). Since Brazil's power sector is already 90% renewable, the energy sector would mainly contribute by producing and using cellulosic biofuels (Figures S8 and S9).

3.5 | Relative economic efforts

Figure 3 shows the economic efforts of our net-zero pathways relative to BASE. The costs from the land-use sector combine opportunity and restoration costs, while the costs from the energy sector are estimated by the BLUES model (Table S16). Between 2020 and 2050, we found that the relative annual costs from the energy sector are 19.4 times higher than those from the land-use sector for the FCNZ scenario. Even under a scenario with full protection and enhanced restoration (FC+NZ), the measures from the energy sector would still be three times more costly than the ones from the land-use sector. Additionally, the measures from the land-use sector (such as protection and restoration) can deliver co-benefits for increasing resilience and adaptation to climate change impacts.

4 | DISCUSSION

In this study, we provide a comprehensive quantitative analysis of how the implementation of existing and expected national policies, mainly from the LULUCF sector, could help Brazil achieve its short- and long-term NDC targets, including the net-zero GHG emissions pledge by mid-century. Our detailed regional IAM approach covers all sectors and Brazilian biomes and explores how policies from the LULUCF sector could influence the burden on other sectors. Although the full implementation of the FC (FC scenario) would be enough for Brazil to fulfil its near-term commitments, it would not bridge the gap to its net-zero pledge by 2050. We reveal that the FC combined with zero legal deforestation and an enhanced large-scale restoration target (FC+ scenario) would also not be sufficient to bridge this gap by mid-century. Nonetheless, under this scenario, Brazil would stay on a clear path towards net-zero GHG emissions by around 2040. Our results highlight the policy gap between Brazil's net-zero pledge and the country's major existing and planned policies. It also points to the need for revising the short-term NDC targets and aligning them with the country's long-term net-zero pledge, otherwise necessary actions could be delayed during this critical decade. A good starting point would be defining, in a new NDC for Brazil, absolute emissions reduction targets equal to or more ambitious than the ones made in Brazil's first NDC (Brazil, 2015).

Our net-zero pathways (FCNZ and FC+NZ scenarios) bridge the gap to net-zero GHG emissions by 2050 by forcing the energy sector to enhance efficiency, increase biofuel use, and deploy costly CDR methods. Since Brazil already has a low-emissions energy system with a large share of hydropower and considerable penetration of biofuels, the highest contribution from this sector is likely to come mainly from BECCS (Köberle et al., 2020, 2022; Tagomori et al., 2023). Moreover, our modelling approach indicates that the energy sector alone is not likely to bridge the gap to net-zero GHG emissions (BASENZ scenario). If the current agricultural practices persist and the government fails to implement actions to halt deforestation and promote large-scale restoration, Brazil will lose any chance of reaching its net-zero pledge due to a high dependency on costly and late negative emissions technologies (Hasegawa et al., 2021). This underscores the crucial role of NbS in establishing a credible net-zero pathway for Brazil.

Other modelling studies have also shown the fundamental role of protection and restoration as cost-effective strategies to reduce emissions in Brazil (De Oliveira Silva et al., 2018; Dumas et al., 2022; Gurgel et al., 2019; Köberle et al., 2020; La Rovere et al., 2018;

Rochedo et al., 2018; Roe et al., 2019, 2021; Schaeffer et al., 2020), reinforcing our conclusions. It is urgent to enforce Brazil's Forest Code and go beyond it. Zero deforestation (both illegal and legal) commitments should be added in law given its lower costs and multiple environmental co-benefits when compared to engineered solutions towards net zero (Cook-Patton et al., 2021; Seddon et al., 2020). The adoption of zero deforestation is also vital to prevent current illegal deforestation from becoming legal in the future. Since ecosystem restoration can take years to several decades to recover carbon stocks, it is pivotal to scale it up without further delay (United Nations, 2019).

More investments in sustainable agriculture practices are also required. The previous agribusiness financing plan (Plano Safra 2022/23), which amounted to 340.88 billion BRL, allocated less than 2% of its budget to low carbon emissions strategies (ABC+ Plan) (Brazil, 2022b). If the adoption of low-emissions agriculture practices exceeds current trends, less BECCS would be needed to bridge the gap to Brazil's net-zero GHG emissions goal. Equally important is developing legislation to support and regulate the deployment of technologies such as BECCS, given the negative impacts they might pose to biodiversity, water, and food availability (Seddon, 2022).

A heavy reliance on engineered solutions would not only jeopardise Brazil's chances of achieving its net-zero pledge but also be more costly. According to our net-zero pathways, the greater the gap to net-zero GHG emissions left by the land-use sector due to less adoption of NbS such as protection and restoration, the higher the costs from the energy sector to bridge this gap. Inevitably, the transition to a net-zero GHG emissions economy will come at a high cost (UNFCCC Race to Zero, 2021). Although the costs of adapting to climate change are beyond the scope of this study, they are also expected to be significant (UNEP, 2021b). By investing in NbS, Brazil will be on track towards its net-zero pledge whilst increasing its resilience to climate change.

As a developing country, Brazil faces financial barriers to implementing its climate plan, which makes international cooperation essential for the country to fulfil its NDC commitments, including the net-zero pledge. The re-activation of the Amazon Fund, based on donations from wealthy nations, represents an important financial mechanism for promoting conservation and sustainable development in the Brazilian Amazon. Other financial opportunities could be created regarding the carbon market mechanism under Article 6 of the Paris Agreement and via a carbon pricing system (Gurgel et al., 2019; La Rovere et al., 2018). Conversely, high deforestation levels have the large potential to push away business development, projects and investments that may otherwise be attracted to Brazil. Emerging due diligence legislations on forest risk commodities, such as the European Union Deforestation Regulation (EUDR), require the elimination of deforestation from production to continue trading with major consumer markets.

According to a global modelling study that evaluates net-zero pathways for major emitting countries (Van Soest et al., 2021), Brazil will reach net-zero GHG emissions by around 2035, that is almost one decade from now. This result is not observed in previous low-emissions trajectories from regional modelling approaches (De Oliveira Silva et al., 2018; Gurgel et al., 2019; Köberle et al., 2020; La Rovere et al., 2018; Rochedo et al., 2018), and in our study. Van Soest et al. (2021) findings are based on global modelling approaches that allow Brazil to anticipate least-cost mitigation efforts to contribute to global net-zero GHG emissions. Repositories like the Global Stocktake tool (Roelfsema et al., 2020) might consider including more regional level studies in their database that investigate the role of local policies.

As with other modelling approaches, ours also have limitations. We do not account for the climate change impacts on Brazil's future trajectories and, consequently, on emissions estimates. Socio-economic issues of large-scale restoration are also out of the scope of this analysis. One caveat is our conservative assumption of fixed carbon removals from native forests during 2020–2050, which could be smaller than those reported in Brazil's future communications to the UNFCCC. On the other hand, various studies widely debate carbon removals from native forests, indicating they are controversial and should be close to zero at a steady state level (Malhi et al., 2015; Pyle et al., 2008; Vieira et al., 2004; Wright, 2013). Additionally, recent analyses revealed that parts of the Amazon already act as carbon sources to the atmosphere instead of carbon sinks (Boulton et al., 2022; Gatti et al., 2021, 2023). Our study also assumes a conservative approach toward evolving technology trends and their adoption in the agricultural sector to reduce GHG emissions. For instance, our modelling approach does not include Integrated Crop-Livestock-Forestry (ICLF) systems (EMBRAPA, 2017; Rede ILPF, 2021), despite considering a significant increase in cattle ranching intensification and cropland expansion under our policy scenarios. Additionally, the forestry component of ICLF systems, crucial for emissions reductions in these production systems, covered less than 2 Mha in Brazil in 2015 (EMBRAPA, 2017). Simultaneously, we have taken a conservative approach toward Agriculture 5.0 technologies (Ragazou et al., 2022) by assuming an exogenous yield increase (Supporting Information), which captures some of these expected technological advances. While beyond the scope of our study, emerging biotechnologies such as lab-cultured meat, algae-based feed and renewable hydrogen-based protein production have the potential to significantly reduce the environmental footprint of food systems. These technologies should be considered in future analyses due to their implications for policy aimed at sustainable food production with significant GHG emissions reduction. More details on the limitations of this study can be found in the Supporting Information.

5 | CONCLUSION

The Paris Agreement aims to strengthen the global response to the climate change crisis. Signatory countries have agreed to revisit their short-term emission reduction targets annually and increase their ambition to put the world on track for a consistent 1.5°C pathway. This year, the global stocktake will help raise overall ambition by assessing the world's collective progress towards this long-term temperature goal. It is time to align the near-term action plans with the long-term net-zero pledges. A net-zero plan for Brazil should consider the urgency of halting deforestation, the need for scaling up investments in sustainable agricultural practices and renewable energy sources, the importance of promoting high-integrity projects to compensate for residual emissions, and the consistency with a just and equitable transition (Fankhauser et al., 2022). To this end, Brazil needs to strengthen and implement existing policies as well as go beyond them. Creating a national plan on net-zero carbon and GHG emissions could scale up the needed ambition. It should aim to align short- and long-term emissions reduction targets and must consider synergies and trade-offs across sectors. Delayed transitions towards net zero will incur higher costs and irreversible impacts, requiring challenging transformations (Drouet et al., 2021; Riahi et al., 2021). They would increase and intensify climate change impacts on ecosystems, undermining conservation efforts and threatening the multiple social, environmental and economic ways nature supports people (Seddon, 2022; Seddon et al., 2020). The failure in implementing and scaling up high-integrity NbS in Brazil, mainly curbing the conversion of carbon rich biodiverse native ecosystems, could also hinder the health and resilience of the country's economy given its high dependence on biodiversity and ecosystem services such as climate regulation, water supply and food provision. Moreover, Brazil harbours around 20% of the world's species, meaning that ongoing ecosystem conversion threatens the integrity of the entire biosphere. By operationalising a credible net-zero pathway, Brazil will help address our societal challenges, build resilience to future climate and socio-economic risks, and play a leading role in the intertwined agendas of climate change and biodiversity.

AUTHOR CONTRIBUTIONS

Aline C. Soterroni: Conceptualization; formal analysis; methodology; visualization; writing – original draft; writing – review and editing. **Mariana Império:** Conceptualization; formal analysis; methodology; writing – review and editing. **Marluce C. Scarabello:** Conceptualization; formal analysis; methodology; writing – review and editing. **Nathalie Seddon:** Conceptualization; methodology; visualization; writing – review and editing. **Michael Obersteiner:** Conceptualization; methodology; visualization; writing – review and editing. **Pedro R. R. Rochedo:** Conceptualization; formal analysis; methodology; writing – review and editing. **Roberto Schaeffer:** Conceptualization; methodology; writing – review and editing. **Pedro R. Andrade:** Visualization; writing – review and editing. **Fernando M. Ramos:** Writing – review and editing. **Tasso R. Azevedo:** Writing – review and editing. **Jean P. H. B. Ometto:** Writing – review and editing. **Petr Havlík:** Writing – review and editing. **Ane A. C. Alencar:** Writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.8399336.

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