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

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Over 130 countries have committed to reaching net-zero CO_2 or GHG emissions by 2050, yet this ambition is rarely underpinned by robust policies. By applying a detailed integrated assessment modelling approach for Brazil, we assess, for the first time, the extent to which the existing and planned local policies could put Brazil on the path to its net zero pledge. This includes quantifying the role of nature-based solutions, such as protection and restoration, and engineered solutions, such as bioenergy with carbon capture and storage (BECCS). We show protection is the single most important climate mitigation measure at relatively low costs, whereas relying heavily on engineered solutions would jeopardise Brazil's chances of achieving its net zero pledge. We also show that the mismatch between Brazil's short- and long-term climate targets reflects current weak environmental governance. Our analysis reinforces the urgent need for Brazil to eliminate illegal deforestation and go beyond to help fight climate change whilst curbing biodiversity loss.

Keywords: Brazil's climate pledges; net-zero emissions; nature-based solutions; mitigation potentials; integrated assessment modelling

Our best chance to limit mean 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 [1,2,3]. Nature-based solutions (NbS), which involve the protection, restoration and sustainable management of natural and semi-natural ecosystems, have the potential to make an important contribution to reaching net-zero CO_2 by around 2050 [4,5,6], if implemented alongside rapid and significant reduction of GHG emissions [7]. Compared to engineered solutions such as carbon capture and storage (CCS), NbS are often less costly and ready to be deployed at scale [8]. If well implemented, NbS can provide multiple co-benefits for both human well-being and biodiversity, reduce the risk of impermanence, and increase ecosystem resilience to climate change impacts [7,8,9].

The Paris Agreement provides an international framework for climate action aiming to keep 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 been submitting 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 decreasing ambition relative to their first NDCs [10,11]. Currently, 136 countries have committed to net-zero CO_2 or net-zero GHG emissions pledges [12], but less than half of these is in law or in policy documents pointing to a gap between promises and action [13]. Moreover, many short-term NDC targets do not meet the ambition of mid-century net-zero goals [14,15].

Brazil, the most biodiverse country on Earth, submitted the first update of its NDC [16] to the UNFCCC allowing a 33% increase in GHG emissions relative to the first NDC [17] (see **Table S1**). Among other serious issues (see **SI**), this NDC violates the progression and non-regression principles of the Paris Agreement [10,18]. During the Glasgow Climate Change Conference (COP26), Brazil announced changes to its climate plan [19,20], later confirmed in the second update of its NDC (hereafter 'Brazil's latest NDC') [21]. It includes a revision to the 2030 target and the anticipation in one decade of its long-term commitment to reaching net-zero GHG emissions by mid-century. Brazil's climate plan was considered insufficient as its pledges, including net zero, need substantial improvements to be consistent with the Paris Agreement's temperature goal [22]. Brazil's latest NDC also fails to incorporate efforts aligned with the Glasgow Leader's Declaration on Forests and Land Use, and the Global Methane Pledge [18]. After COP26, the official monitoring system PRODES [23] released a 15-year high deforestation rate in the Brazilian Amazon with the forest clear-cut above 10,000 km^2 for the third consecutive year.

Land-use change, which includes deforestation, is a large source of GHG emissions, a major driver of biodiversity loss and a threat to ecosystem health and resilience. While the Land Use, Land-Use Change and Forestry (LULUCF), and agricultural sectors contribute to one-third of global gross GHG emissions [9], they account for almost three-quarters in Brazil [24]. In 2020, the LULUCF sector alone was responsible for almost half (46%) of Brazil's gross GHG emissions with almost 90% of it caused by deforestation [24]. Brazil is one of the world's top GHG emitters [25] and has a historical responsibility [26] with its emissions mainly coming from deforestation rather than the burning of fossil fuels. Only 12% of Brazil's original Atlantic Forest biome remains [27], almost half of the Cerrado is gone [28] and about one-fifth of the primary forest in the Amazon biome has been deforested [23,29]. Recent analyses have shown that parts of the Amazon are already acting as carbon source to the atmosphere instead of carbon sink [30,31].

Here we quantify the gap to net-zero GHG emissions by mid-century and estimate the contribution of key mitigation measures that are able to put Brazil on the path towards its net zero GHG pledge. To this end, we combine two well-established and detailed models for the country (the regional economic partial equilibrium land use model GLOBIOM-Brazil [32,33], and the process-based, integrated assessment model BLUES [34]) to design locally meaningful policy scenarios (see **Table 1** and **Methods**) and project emissions from all sectors of the economy up to 2050. Other national-level modelling studies consider few dispositions of key national policies such as the Forest Code [35], specific sectors [36] or used global models and scenarios that are not validated against Brazilian official statistics for the historical period [4,37,38,39] (see **Validation** section in **SI**).

Table 1: Overview of scenarios.

Scenario name	**Short description**	**Net-zero GHG target by 2050**	**Additional mitigation measures relative to BASE**
Baseline (BASE)	This scenario has a weak environmental governance. During this decade (2020-2030), deforestation follows the current levels. There is no native vegetation restoration. Agricultural practices also follow current trends. The energy sector considers agreed and installed	No	-

	infrastructure, and energy policies currently in place.		
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 as identified in the Rural Environmental Cadastre (CAR) dataset excluding environmental debts in small farms.	No	Illegal deforestation control; native vegetation restoration (approx. 13 million hectares).
Forest Code Plus (FC+)	Built upon FC, this scenario goes beyond the Forest Code eliminating both illegal and legal deforestation whilst promoting more than a twofold increase in native vegetation restoration relative to the FC. Illegally deforested areas, including the amnesty from small farms, are restored.	No	Legal and illegal deforestation control; native vegetation restoration (approx. 35 million hectares).
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 net zero GHG in a cost-effective way.	Yes	Negative emissions technologies such as BECCS.
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 net zero GHG in a cost-effective way.	Yes	Illegal deforestation control; native vegetation restoration (approx. 13 million hectares); negative emissions technologies such as BECCS.
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 net zero GHG in a cost-effective way.	Yes	Legal and illegal deforestation control; native vegetation restoration (approx. 35 million hectares); negative emissions technologies such as BECCS.

Results

Our baseline (BASE) scenario attempts to capture a weak environmental governance in Brazil. Under this scenario, projected net emissions are quite flat between 2020 and 2050 (see **Fig. 1**). Despite the high level of uncertainty in carbon sequestration from the land use sector (see **Table S2**), our net GHG emissions estimates account for carbon removals from secondary forest regrowth and protected areas following the latest available national emissions inventory [40] regardless of the scenario (see **Methods**). Under the BASE scenario, emissions increase from the agricultural and energy sectors are balanced by emissions reduction from the LULUCF sector (see **Fig. S1**). Although emissions from the LULUCF sector decrease, native vegetation losses (hereafter 'deforestation') continue up to 2050 (see **Fig. S2**). During this decade (2020-2030), deforestation in Brazil is expected to reach 29,170 km^2 per year, on average, with 36% (or around 10,590 km^2 per year) projected to take place in the Amazon biome, a similar figure observed in recent years [23]. Between 2030 and 2050, accumulated deforestation in the Amazon and Cerrado biomes would compare to the size of the United Kingdom (26 million hectares) (see **Table S3**). Built upon the BASE, the Forest Code (FC) and the Forest Code Plus (FC+) scenarios evaluate the role of policies aimed at avoiding deforestation and promoting large-scale native vegetation restoration (hereafter 'restoration') in Brazil's net zero pledge. The impacts of these scenarios on land-use changes and major agricultural commodities can be seen in **Figs. S2-S5**.

Gap to net-zero GHG emissions

Brazil's gap to net-zero GHG emissions by 2050 would be 1,472 million tonnes of carbon dioxide equivalent (MtCO$_2$e) under the BASE scenario (see **Fig. 1** and **Table S4**). Full implementation of the Forest Code (FC scenario) bridges over one-third (37%) of the gap to net-zero GHG emissions by 2050, decreasing overall emissions from 1,472 to 922 MtCO$_2$e (see **Fig. 1** and **Table S5**). 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 58% relative to the BASE scenario amounting to 614 MtCO$_2$e of net emissions by 2050 (see **Fig. 1** and **Table S6**). Brazil would be below or close to a linear path towards net zero up to 2030 under the FC scenario, and up to 2040 under the FC+ scenario. Nevertheless, the emissions reductions from both the FC and FC+ scenarios would not be enough to reach net-zero GHG emissions by mid-century.

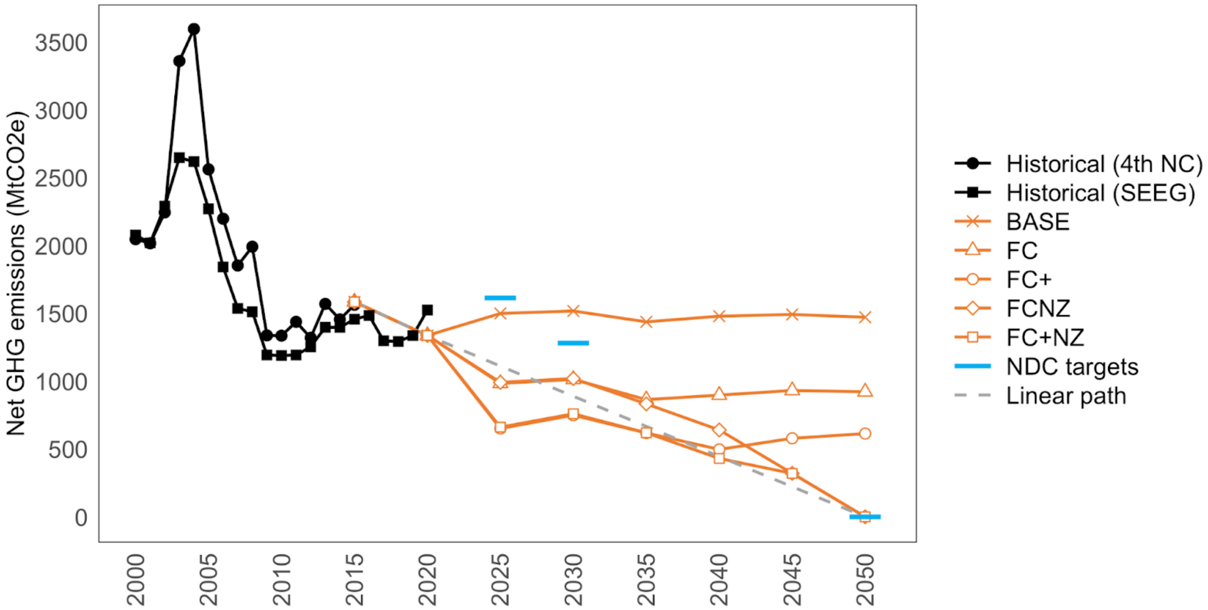


Figure 1: Brazil's future net GHG emissions for all sectors. *Brazil's net GHG emissions trajectories (2015-2050) as projected by the various scenarios. Yearly historical emissions are from Brazil's 4th National Communication to the UNFCCC (4th NC) [40] and the Greenhouse Gas Emission and Removal Estimating System (SEEG) Initiative [24]. 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) are indicated in blue. A linear path towards net zero starts in 2015. Values are in million tonnes of carbon dioxide equivalent (MtCO$_2$e) using GWP$_{100}$ from IPCC AR5.*

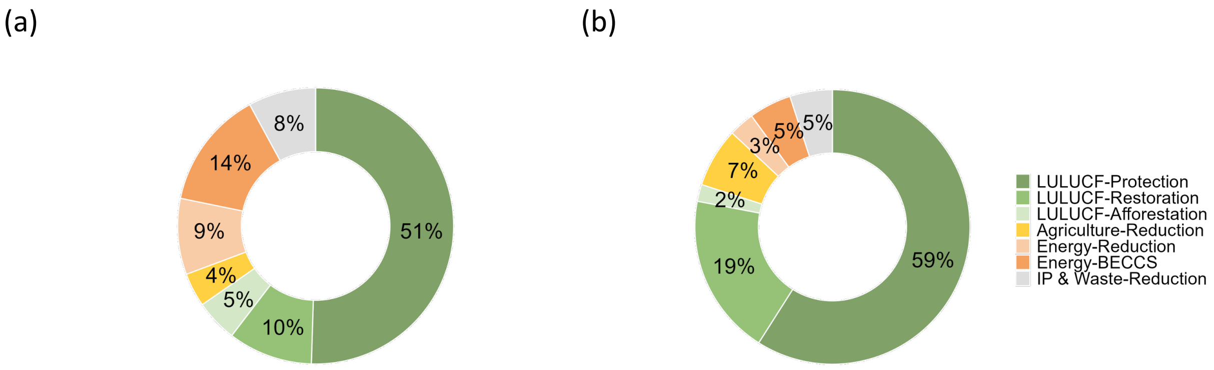
Mismatch between short- and long-term targets

By construction, the gap to net-zero GHG emissions left by the BASE, FC and FC+ scenarios is bridged by the energy sector (see **Tables S7** and **S8**). However, our modelling approach suggests an infeasible trajectory towards net zero under the baseline scenario (BASENZ). 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 bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC). However, these engineered solutions are not able to compensate for the emissions from the LULUCF and agricultural sectors. Without reducing deforestation, Brazil will not reach net-zero GHG by 2050. Conversely, Brazil's short-term 2025 NDC target is likely to be achieved under the BASE scenario (see **Fig. 1**). By 2030, the country would not reach its NDC goal by 237 MtCO$_2$e or only 11% of the country's gross emissions projected for that year, which would not require huge efforts to overcome (see

Fig. 1). The BASE pathway that might be enough to fulfil the latest NDC short-term targets is incompatible with Brazil's long-term net zero pledge.

Mitigation potential of key activities

Figure 2 shows the mitigation potential of key activities and sectors as projected by the net zero scenarios FCNZ and FC+NZ relative to the BASE scenario for 2020-2050. Mitigation potential from the LULUCF sector is broken down into protection, restoration and afforestation. The energy sector's mitigation potentials are divided into BECCS and reduced emissions due to greater use of renewables and efficiency increase. Mitigation potential from the agricultural sector accounts for emissions reduction from degraded pasture recovery and decrease in production due to trade-offs with land-use policies, both excluding related land-use changes to avoid double counting.



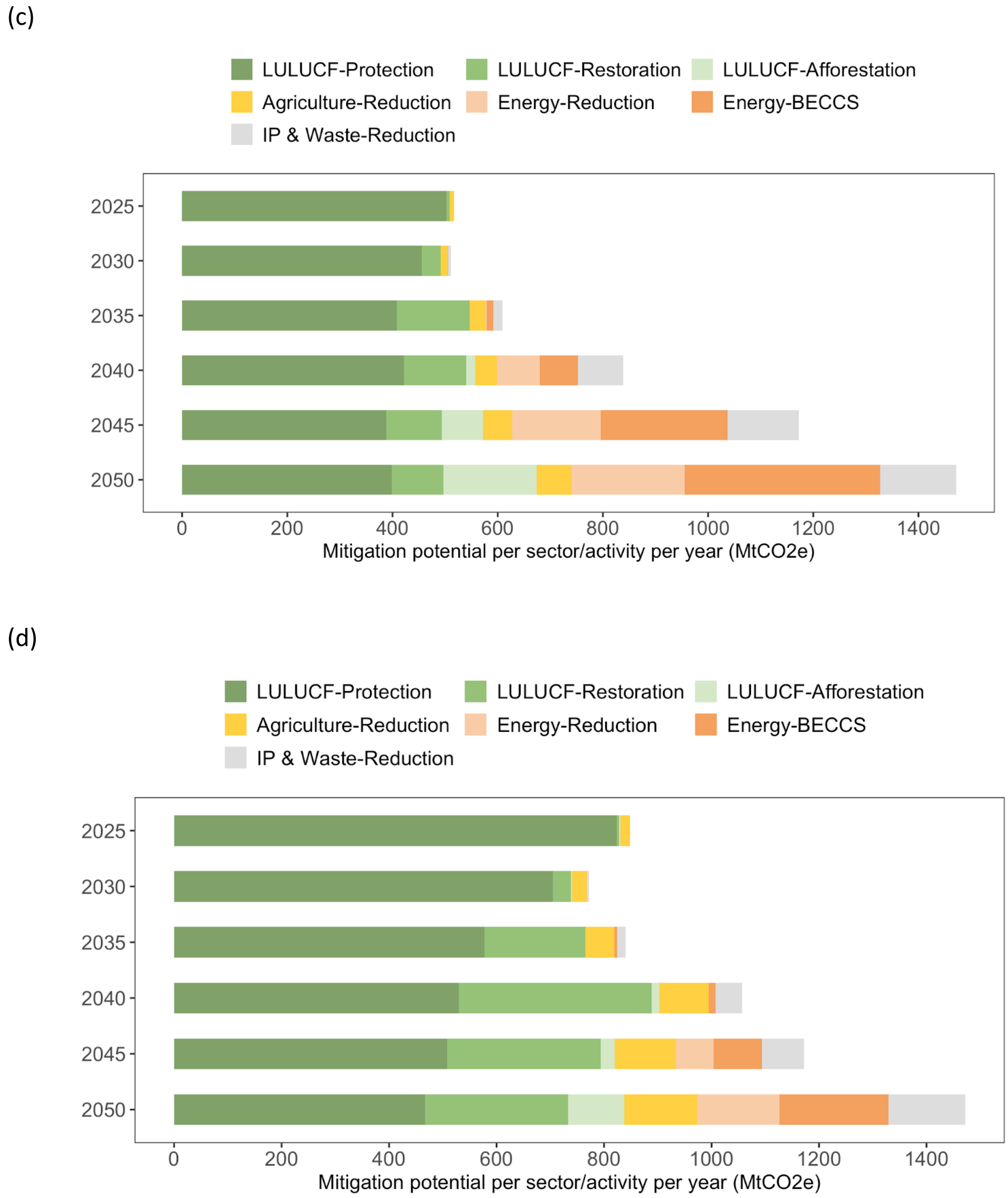


Figure 2: Mitigation potential by sector and key activities. *Accumulated mitigation potential over the period 2020-2050 for the scenarios (a) FCNZ and (b) FC+NZ relative to the BASE scenario. Mitigation potential evolution per year relative to the BASE scenario for different sectors and key activities as projected by the scenarios (c) FCNZ and (d) FC+NZ. Values are in million tonnes of carbon dioxide equivalent (MtCO$_2$e) using GWP$_{100}$ and IPCC AR5.*

Protection has the highest contribution among all considered measures. Between 2020 and 2050, it could provide from 51% (FCNZ) to 59% (FC+NZ) of the necessary CO_2e mitigation for Brazil to achieve net-zero GHG emissions by mid-century (see **Figs. 2a** and **2b**). When compared to BASE, protection alone could prevent the release of 12,878 $MtCO_2e$ according to the FCNZ scenario, and 18,050 $MtCO_2e$ as projected by the FC+NZ scenario (see **Table S9**). Moreover, protection contributes more than any other mitigation measure per year with a particularly important role in decreasing Brazil's emissions in the near term. During this decade, more than 90% of the overall emissions reduction would be due to protection (see **Fig. 2c** and **2d**). Zero illegal deforestation (FCNZ scenario) has the potential to mitigate 429 $MtCO_2e\ yr^{-1}$, on average, between 2020 and 2050, while preventing both illegal and legal deforestation (FC+NZ scenario) would mitigate 602 $MtCO_2e\ yr^{-1}$, on average, during the same period.

Here we distinguish between afforestation and native vegetation restoration. Between 2020 and 2050, the mitigation potential of restoration varies from 10% (FCNZ) to 19% (FC+NZ) amounting to 2,513 $MtCO_2e$ and 5,688 $MtCO_2e$, respectively, of carbon uptake over this period (see **Fig. 2a** and **2b**, and **Table S9**). Carbon storage can take from years to decades to be accumulated by ecosystems and, based on our scenarios, restoration also follows the schedule of Brazil's national plan for native vegetation recovery (PLANAVEG) from 2021 onwards [41]. Although restoration would provide a limited mitigation potential in the first decade (2020-2030), it offers up to 139 $MtCO_2e$ of carbon uptake under the FCNZ scenario (**Fig. 2c**) by 2035, and up to 359 $MtCO_2e$ by 2040 according to the FC+NZ scenario (**Fig. 2d**). Moreover, well-designed ecosystem restoration goes beyond carbon and includes biodiversity conservation, provision of ecosystem services and improvement of local livelihoods [42,43].

Protection and restoration as defined in our policy scenarios involve trade-offs with agriculture (see **SI**). Reduction in agricultural production relative to the BASE scenario is expected even though agricultural intensification is performed by the model, including livestock intensification and expansion of double cropping for soy and maize (a type of no-till farming). Between 2020 and 2050, the agricultural sector would mitigate from 4% to 7% 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 (see **Fig. 2a** and **2b**). It amounts to 1,076 $MtCO_2e$ under the FCNZ and to 2,206 $MtCO_2e$ under the FC+NZ during the period 2020-2050 (see **Table S9**).

Under our scenarios, efforts needed from the energy, industrial processes (IP) and waste sectors are likely to be defined by 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 31% under the FCNZ scenario (see **Fig. 2a**), decreasing to 13% under the FC+NZ scenario (see **Fig. 2b**). It would represent an emissions reduction of 7,668 $MtCO_2e$ under the FCNZ, and 3,847 $MtCO_2e$ under the FC+NZ during the same period (see **Table S9**). Note that the energy sector's mitigation potential is unevenly distributed over time (see **Fig. 2c**, **Fig. 2d** and **Fig. S6**). By 2050, the CO_2e mitigation needed from the energy sector alone amounts to 40% (587 $MtCO_2e$) under the FCNZ scenario, and 24% (356 $MtCO_2e$) under the FC+NZ scenario, with the majority of those contributions coming from BECCS (see **Fig. S7**). Since Brazil's power sector is already 90% renewable, the energy sector would mainly contribute through the production and use of cellulosic biofuels (biomass-based) (see **Fig. S8** and **S9**).

Under the BASE scenario, afforestation through tree-planting would cover an area of 16 million hectares in Brazil by 2050 and sequester 1,718 $MtCO_2e$ between 2020 and 2050 (see **Table S9**). Under the net zero scenarios, afforestation follows the BASE trends, which makes the relative mitigation potential small. As the need for BECCS increases the demand for biomass feedstock from planted forests, afforestation mitigation potential increases under FCNZ (5%) and FC+NZ (2%) scenarios (see **Fig. 2a** and **Fig. 2b**), amounting to 3,052 $MtCO_2e$ and 2,464 $MtCO_2e$, respectively, for the period 2020-2050 (see **Table S9**).

Relative economic costs

To give an estimate of the economic efforts from the land use (LULUCF and agriculture) and energy sectors under our policy scenarios, we calculate relative costs to the BASE scenario. The relative costs from the land use sectors combine opportunity costs and restoration implementation costs (see **Methods** and **Table S10**). The relative costs from the energy sector include additional investments in energy efficiency, innovative technologies and negative emissions options such as BECCS (see **Methods**). As can be seen in **Fig. 3**, between 2020 and 2050, the relative annual costs from the energy sector are much higher than the costs from the land use sector for the FCNZ scenario. Under a scenario with full protection and enhanced restoration (FC+NZ), the differences between both sectors are smaller but the energy sector would still be more costly than the land use sector.

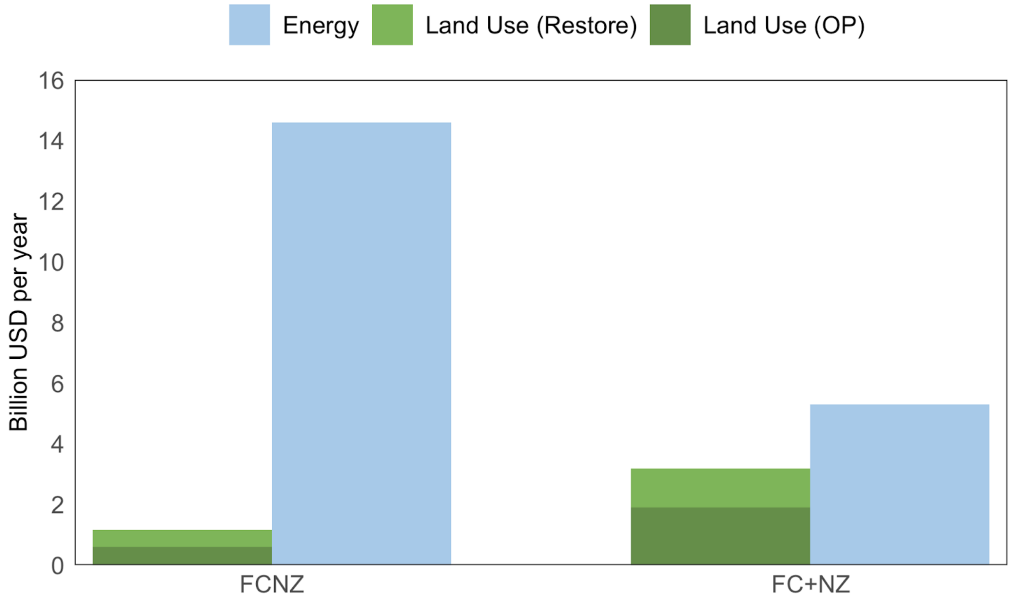


Figure 3: Relative costs under scenarios that bridge the gap to net zero. *Relative costs in billion USD per year during the period 2020-2050 as projected by the FCNZ and FC+NZ scenarios. Costs from the land use sector consider opportunity costs (OP) and restoration implementation costs. Costs from the energy sector take into account the increase in energy efficiency and deployment of negative emissions technologies such as BECCS. We are using an annual discount rate of 5% over the period 2020-2050 and US$$_{2019}$ currency.*

Discussion

The Paris Agreement aims to strengthen the global response to the climate change crisis. It is essential for the integrity of this climate pact that common but differentiated contributions are perceived as fair and real by all Parties aiming for the highest possible ambition. Brazil's latest NDC short-term targets do not represent an increase in ambition over time and the country's long-term commitment is not backed by a robust net zero plan. We have shown that Brazil is likely to reach its near-term targets, but would reach its net-zero GHG emissions by mid-century with an estimated gap of 1,472 $MtCO_2e$ under the BASE scenario that attempts to capture the country's current weak environmental governance. This points to the mismatch between the country's short and long-term pledges and the risk of climate inaction by the government during this critical decade. If actions to halt deforestation and promote large-scale restoration are not implemented alongside the maintenance of the current agricultural practices, Brazil would lose any chance of reaching its net zero pledge due to a high dependency on costly and late negative emissions technologies such as BECCS.

Nature-based solutions, especially protection, are critical for putting Brazil on track for its net zero pledge. Avoiding deforestation is the most effective strategy to rapidly reduce emissions in the country, especially during this decade, and should be prioritised. If a weak environmental governance continues, an area comparable to the size of France (64 million hectares) of native ecosystems is likely to disappear during the next 30 years in Brazil (see **Table S3**). Around 38% of this deforestation would take place in the Brazilian Amazon, threatening its vast biocultural diversity and raising global environmental concern as the Amazon basin approaching a tipping point has consequences for the whole planet [29,30,31]. Brazil's Cerrado, a tropical savanna and a global biodiversity hotspot, would also be under threat since 39% of the projected deforestation is likely to happen within this already largely exploited biome. Compared to other mitigation measures, protection is readily available to be implemented. It would not require several decades to recover carbon stocks (as restoration), would not cause negative environmental impacts (as afforestation) and is less costly in the long-term than engineered solutions.

Although full implementation of the Forest Code has the potential to put Brazil's short-term goals on track for its long-term net zero pledge during this decade, it would reduce the gap to net-zero GHG emissions by only 36%, requiring significant investments in negative emissions technologies. If Brazil is to reach net-zero GHG emissions by 2050, some extent of negative emissions technologies, such as BECCS, will be unavoidable. The amount of engineered solutions will be defined by the mitigation efforts from the LULUCF and the agricultural sectors. Additional measures from the LULUCF sector, including zero legal deforestation, would put Brazil under a linear trajectory towards net zero up to 2040, demonstrating the need to eliminate deforestation (illegal and legal) from the land-use sector. While zero illegal deforestation will require implementation and strengthening of existing laws, especially to avoid enabling current illegal deforestation from becoming legal deforestation in the future, zero legal deforestation will require efforts and incentives beyond the current policies.

As a developing country, Brazil faces financial barriers to the enforcement of environmental laws. International cooperation will be essential for the country to halt deforestation and achieve its net zero pledge. Financial opportunities could be created regarding the carbon market mechanism under Article 6 of the Paris Agreement. Conversely, the current 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 soy and beef will require the elimination of both illegal and legal deforestation if Brazil wishes to continue trading with major consumer markets [44].

At COP26, signatory countries agreed to annually revisit their short-term emission reduction targets and increase their ambition to put the world on track of a consistent 1.5°C pathway. In 2023, the first global stocktake will assess the world's collective progress towards this long-term temperature goal and help to raise overall ambition. It is time to align the near-term action plans with the long-term net zero pledges. Delayed transitions towards net zero pathways will require challenging transformations, which will be more expensive and will be accompanied by irreversible impacts [45,46]. They would increase and intensify climate change impacts on ecosystems jeopardising the permanence of biological storage and, more importantly, undermining conservation efforts and threatening the multiple social, environmental and economic benefits nature provides [7,8].

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Competing interests

The authors declare no competing interests.

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Methods

In this work we combine the regional economic partial equilibrium model GLOBIOM-Brazil [32,33] and the process-based, integrated assessment model BLUES [34] to project Brazil's GHG emissions for all sectors and various policy scenarios. Emissions from the LULUCF and agricultural sectors are projected by the GLOBIOM-Brazil model, and emissions from the energy, industrial processes (IP) and waste sectors are projected by the BLUES model. Both models are regional versions of global models for Brazil, meaning they have better input data, resolution, calibration and validation against official statistics. Since regional models capture local specificities in much greater detail than global models, they also allow the construction of real policy scenarios. Firstly, we run GLOBIOM-Brazil for a given policy scenario and, then, the emissions outputs from GLOBIOM-Brazil are used as input data into the BLUES model. By construction, the net zero scenarios are expected to achieve net-zero GHG emissions by 2050 in Brazil by allowing the BLUES model to optimise Brazil's energy system and generate the amount of negative emissions needed to offset remaining positive emissions from the LULUCF and agricultural sectors. A brief description of each model, emissions estimates and cost calculations for this study are given as follows.

Land use modelling (GLOBIOM-Brazil model)

GLOBIOM-Brazil [32,33] is based on the global bottom-up, partial equilibrium, land-use model GLOBIOM [47]. GLOBIOM-Brazil and GLOBIOM have identical data sets and the modelling approaches for regions outside Brazil. Within Brazil, GLOBIOM-Brazil has been adapted to incorporate Brazil's specificities and local policies [32,33,48,49]. Like GLOBIOM, GLOBIOM-Brazil simulates the competition for land among agricultural, forestry and bioenergy sectors subjected to resource, technology and policy restrictions. Land-use changes, which include deforestation, are not imposed on the model but are a result of the market signals combined with land suitability, biophysical information, production and land conversion costs, resources, technology and policy restrictions. Mathematically, the competition for land is simulated at the pixel level

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by maximizing the welfare (i.e., the sum of consumer and producer surpluses). As a result of the optimization process, the final demand, processing quantities, and trade at the equilibrium state are obtained for each product and region. The prior demands for all regions and products 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) [50]. Here, we use the "middle of the road" SSP2, which implies a future with moderate challenges to mitigation and adaptation. The SSP2 projects a 28% growth in population and a 174% growth in GDP for Brazil between 2000 and 2030. According to the Brazilian Institute of Geography and Statistics (IBGE), Brazil's population is expected to increase 29% by 2030. GLOBIOM-Brazil is recursively dynamic and runs with 10- or 5-year time steps, starting at the baseline year of 2000. Here, we ran GLOBIOM-Brazil with 5-year time steps. The model is geographically represented by a uniform grid of 0.5° x 0.5° within Brazil (approximately 50km x 50km at the Equator) and 2° x 2° outside Brazil (approximately 200km x 200km at the Equator). In this study, GLOBIOM-Brazil was updated to use the Collection 4.1 of the Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomas), which has become a reference map for Brazil [28]. More details in the **SI**.

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

BLUES (Brazilian Land-Use and Energy System) [34] is a minimum cost optimization 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 2050 in 5-year intervals, minimising the total cost of the system, 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 represented in detail 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 and they are based on the SSP2 pathway [50], using elements such as GDP and population growth forecasts. 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 certain alternatives or environmental and social costs. The model minimises

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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 [51], in this paper 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.

Convergence process between GLOBIOM-Brazil and BLUES models

Since Brazil's decarbonization would encompass an increase in biomass feedstock demand, and this production requires land to grow, it is important that the area required by the biofuels demand in BLUES is appropriately accounted for in GLOBIOM-Brazil. Thus, the additional areas of 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 are defined by the competition for land and the biophysical parameters from GLOBIOM-Brazil. As the energy forests also sequester CO_2, they influence the LULUCF total emissions calculated by GLOBIOM-Brazil and, consequently, the emissions gap that BLUES has to bridge towards net-zero GHG emissions. Our convergence process accepts a difference within 10% 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. All emissions related not only from this production, but also for other uses, were quantified by the GLOBIOM-Brazil model.

Emissions calculations (LULUCF and agricultural sectors)

Emissions from the LULUCF and agricultural sectors are estimated by GLOBIOM-Brazil [32]. The model accounts for CO_2 emissions and removals due to land-use changes and non-CO_2 emissions, including N_2O emissions from fertiliser use, CH_4 from rice cultivation, CH_4 from enteric fermentation, and CH_4 and N_2O from manure management (see **Table S11**). Non-CO_2 emissions are expressed as CO_2e using GWP_{100} in AR5. Here we also take into account emissions reduction from recuperation of degraded pastures [52] by 1 tC/ha/yr [53]. CO_2 emissions or removals from the LULUCF sector are determined by the difference in the carbon content (above- and belowground biomass) between the original class and the new class. Deforestation and native vegetation losses cause CO_2 emissions (positive emissions). Afforestation of planted forests (eucalyptus, pinus, etc) and native vegetation restoration sequester CO_2 (negative emissions). In GLOBIOM-Brazil, the CO_2 release from the terrestrial biosphere to the atmosphere occurs in one simulation period (5-year time step). CO_2 sequestration from afforestation also occurs in one simulation period. On the other hand, CO_2 removals from restoration could take years to several decades depending on the vegetation type. In the Amazon and Atlantic Forest biomes, forest regeneration takes 25 years to recover 70% of the original biomass [54]. For the other biomes, we follow the methodology defined in Soterroni et al. [32], 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), and the grassland-based vegetation of the Pampa biome is assumed to regenerate in 3 years (or one time step). Carbon stock information comes from different biomass maps (see **Table S11**). For Brazil, we mainly use the carbon content (above- and below-ground biomass) from the 3rd Brazil's Emissions Inventory [55]. GLOBIOM-Brazil does not take into account carbon removals by secondary vegetation growth and mostly undisturbed native forests in protected areas. In this case, we follow Brazil's latest national communications (NCs) to the UNFCCC. Dead wood, litter, and soil organic carbon are not considered in our estimates.

Emissions calculations (carbon removals by native forests)

According to IPCC guidelines [56], CO_2 removals from managed forests are allowed in the countries' national emissions inventories, and Brazil classifies its forests within conservation units and indigenous lands (or simply protected areas) as managed forests due to ongoing human interventions necessary to protect those areas. The high uncertainty on carbon removals from native vegetation can be illustrated by the significant differences in official statistics and national communications (NC) to UNFCCC (see **Table S2**). According to Brazil's 4th National Communication to the UNFCCC (4th NC) [40], the latest available and used here to define the NDC absolute targets, the annual average CO_2 removals derived from the CO_2 removal matrices amounts to 610 $MtCO_2$ for the period 2002-2010, and 522 $MtCO_2$ for the period 2010-2016 [57]. Carbon removal estimates from the independent Greenhouse Gas Emission and Removal Estimating System (SEEG) [24] are quite flat and amount to 620 $MtCO_2yr^{-1}$, on average, between 2014 and 2020. 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 the period 2010-2016 (522 $MtCO_2$ per year). By 2045, Brazil's LULUCF sector is likely to become net negative mainly due to these removals despite the weak deforestation control measures encompassed in our BASE scenario (sum positive and all negative emissions from the LULUCF sector in **Table S4**). If the carbon removals by native vegetation were higher or if they increase over time, Brazil's LULUCF sector will become net negative before 2045 under the same trajectory.

Emissions calculations (Energy, IP and waste sectors)

Emissions from the energy, waste and IP sectors are projected by the optimization model for Brazil's energy and land-use systems BLUES [34]. The model calculates CO_2, CH_4 and N_2O emissions individually, as well as a total GHG emissions, using GWP_{100} in AR5 to express it as CO_2e. Energy emissions cover production and transformation of the energy carriers as well as emissions derived from fossil fuels combustion at the end use sectors. On the energy production side, it includes the exploration and production of oil and gas, coal mining, electricity production, refining of oil products and distilleries. It also accounts for fugitive emissions, process emissions on the production of hydrogen and for the sequestration of CO_2 when there is use of CCS applied to the energy production technologies. This may lead to a reduction of CO_2 emissions when applied to fossil fuels consumption as natural gas and coal power plants, for instance, or to the negative emissions when associated with the bioenergy with carbon capture and storage (BECCS), as in the case of ethanol production and biomass to liquids (BTL) plants. On the end use sectors, it encompasses passenger and freight transportation, industry detailed in 11 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 covers emissions from the treatment of urban solid waste, health solid waste and effluent residues. It accounts for emissions from dumping grounds, landfills, composting, biodigestion, incineration and recycling. Industrial processes emissions refer to emissions not related to the combustion of fossil fuel, but from the chemical reactions derived from chemical products fabrication, for instance. Most of them come from chemical, cement and iron and steel subsectors.

Economic costs calculation

The needed economic efforts from the land use (LULUCF and agriculture) and energy sectors to bridge the gap to net zero (FCNZ and FC+NZ scenarios) are given by relative costs to the BASE scenario. Costs from the land use sector are estimated as the combination of restoration implementation costs [58] and opportunity costs based on GLOBIOM-Brazil outputs and commodities prices [59]. The costs from the energy sector are estimated by the BLUES model. To standardise prices among our modelling approach and external information, we use $US\$_{2019}$ currency (US$1.00 = R$4.03) based on the General Price Index - Internal Availability (IGP-DI) from Fundação Getúlio Vargas for December 2019. We use annualised costs over the period 2020-2050 by considering a 5% discount rate per year. Furthermore, as the standard currency in BLUES is $US\$_{2010}$, we used the Chemical Engineering Plant Cost Index (CEPCI) as a dollar inflationary factor [60].

The opportunity costs of implementing net zero policies are estimated based on the reduction in agricultural production relative to the BASE scenario multiplied by the price of Brazil's major commodities (soybeans, maize, sugarcane and beef). Decrease in production is mainly due to deforestation control and for setting aside land for restoration. We consider an average price for each commodity based on annual prices from CEPEA/USP [59], between 2017 to 2022, adjusted by GLOBIOM-Brazil changes in prices under net zero scenarios relative to the BASE. Total restoration implementation 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 (see **Table S12**) following the estimates from [58]. The final average restoration costs are weighted by PLANAVEG scenarios (high, moderate, low and very low) per biome (see **Table S13**). Restoration area is given by the increment in native vegetation restoration area as projected by GLOBIOM-Brazil model for the FCNZ and FC+NZ scenarios, following the PLANAVEG schedule from 2021 to 2050 (see **Tables S14** and **S15**).

BLUES model calculates the total cost of the energy and land use systems. Since we have run the analysis using the GLOBIOM-Brazil to perform the LULUCF and agricultural sectors, we have neglected BLUES cost for the land use systems and we have focused on the energy one. BLUES considers capital expenditures (CAPEX) and operational and maintenance (O&M) costs for all technologies in the model. Costs include exploitation of the energy resources, construction of power utilities, electricity transmission and distribution, installation of refineries facilities, the fuels and biofuels production, and transport of energy carriers. It also includes technologies at the end-use sectors, such as appliances in the households, vehicles in the passenger and transport sectors, costs of different waste treatments technologies and industrial processes, among others. Early-stage technologies costs decrease over time according to the learning curve of each option.

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