Supplementary Online Material

The threat of political bargaining to climate mitigation in Brazil

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This supplementary material contains the description of the Land-use and Energy-system models developed and applied in this study. It also presents the Scenario Building Procedure and more detailed results of the simulations made, including the georeferenced description of the land-use change, the composition of the energy mix and an analysis of the uncertainties of associated with the findings.

S1. Supplementary Methods

This section addresses the methodological procedure of this study. Firstly, the scenarios developed and assessed in this study are presented, especially with regards to the causality from politics to environmental governance and, finally, to land-use change. In order to assess the impact of such causal chain of events under the commitment of the Paris Agreement, the national share of the carbon budget related to limiting the increase in average temperature under 2°C is discussed. Then, the modelling procedure is presented, followed by the description of the two models used in this assessment: OTIMIZAGRO and BLUES.

Scenario Building Procedure

In this paper, we assessed the implications of the CO_2 emissions expected in different levels of environmental governance, with respect to land-use change, in Brazil. In this study we define environmental governance as the capacity of the government and civil society to enforce the institutional arrangement to control deforestation. In this sense, institutional arrangement includes enforcing the rule of law and sending signals that may directly or indirectly incentivize economic agents to curb deforestation. According to this definition, deforestation is the resultant of several forces.

The first link of our methodological causal procedure is from politics to land-use governance. Then, the politics/land use governance link drives the second link, which is related to land-use change scenarios. Finally, these land-use change scenarios drive the causal link between energy, land-use and GHG emissions.

Regarding the link between politics and land-use governance, there is a growing literature showing how specific policies by the Brazilian government and actions from the private sector led to the drastic reduction of deforestation rates in the Amazon in the 2005-2010 period. These include: the increase in the number of fines and changes in law enforcement strategies[24-25], the creation of new protected areas[26], and the soy deforestation moratoria[27].

While the establishment and effectiveness of stronger environmental policies in Brazil (enabled by a favorable political context, see below) are well documented, few studies have analyzed why deforestation has been going up again since 2012. The new Forest Code approved in 2012 during the Dilma Rousseff administration, which provided an amnesty to 58% of all areas illegally deforested before 2008, could incentivize future clearings[28]. The decline in environmental governance in Brazil is linked to a deep political crisis[8], which started with the widespread social mobilizations in 2013, led to the impeachment of president Rousseff in May 2016, and was deepened with criminal charges against President Temer in May/September 2017. For a general appraisal about the relationship between the political systems and climate policies among major players in the climate arena[29].

To explain how the political crisis has been a major driver of increased deforestation and carbon emissions in Brazil in the 2014-17 period, we first analyze the evolution of environmental governance in the Amazon since before the political crisis. By doing that, we can divide the last two decades of environmental governance in the Amazon into three major periods:

1- pre-2005, with very poor governance despite the passage of some important laws that were not implemented;
2- 2005-2010, with dramatic improvement in the governance (good governance) and very effective results in reducing deforestation; and
3- 2011-2017, the stagnation of deforestation reduction policies and growing political signals incentivizing new clearings led to a gradual erosion of the governance (poor governance), the end of the deforestation reduction trend in 2012 and a sharp increase in deforestation during the 2015-17 period.

Pre-2005 period: Very Poor governance of deforestation

The power of environmentalism in the government coalition was null until 1998. Starting in 1999, a timid presence of environment ministers related to the environmental movement began, though quite weak in overall government decisions. The relevance of climate change and the Amazon in society perceptions was low and the environmental agencies in the country had a weak institutional capacity to control deforestation - poorly qualified personnel, restricted use of GPS and monitoring systems. Therefore, before 2005, the very poor governance of deforestation was not related to a political crisis: the major problem derived from the fact that deforestation had not yet reached a critical mass to become a relevant issue in the Brazilian society, and in the government, particularly.

Period 2005-2010: Good governance, building up and strengthening of environmental governance.

This is a period of gradual and steady improvement in environmental governance due to: the increasing importance of the climate issue; the entry into force of the Kyoto Protocol, in 2005; the relative strengthening of the Minister of the Environment at the time (Marina Silva); the gradual increase in the approval rate of the government; and the satisfaction of society with the country's course due to economic growth well above the average of the 1990-2004 period. Even though the environment had not been an issue for President Lula's (2003-2010) previous upward political trajectory, he was ideologically flexible / pragmatic and willing to take on new positions whenever his and his party's power increased. Since 2005 Lula has partially incorporated the climate and Amazonian agenda, which peaked in November 2009, when he decided in favour of his environment minister, against other ministries, in defining the Brazilian position at the Copenhagen Conference of the Parties of the UNFCCC. Throughout the period, the environmental protection agency (IBAMA) increased its institutional robustness with significant new hires of technically qualified employees and new systems for monitoring and technical training. For instance, the share of graduate level employees rose from 41% in 2004 to 52% in 2007[31,32]. The number of fines with geographical coordinates, an important indicator of the quality of the legal case against deforesters[25], increased from almost zero to half of the total (see Figure below).

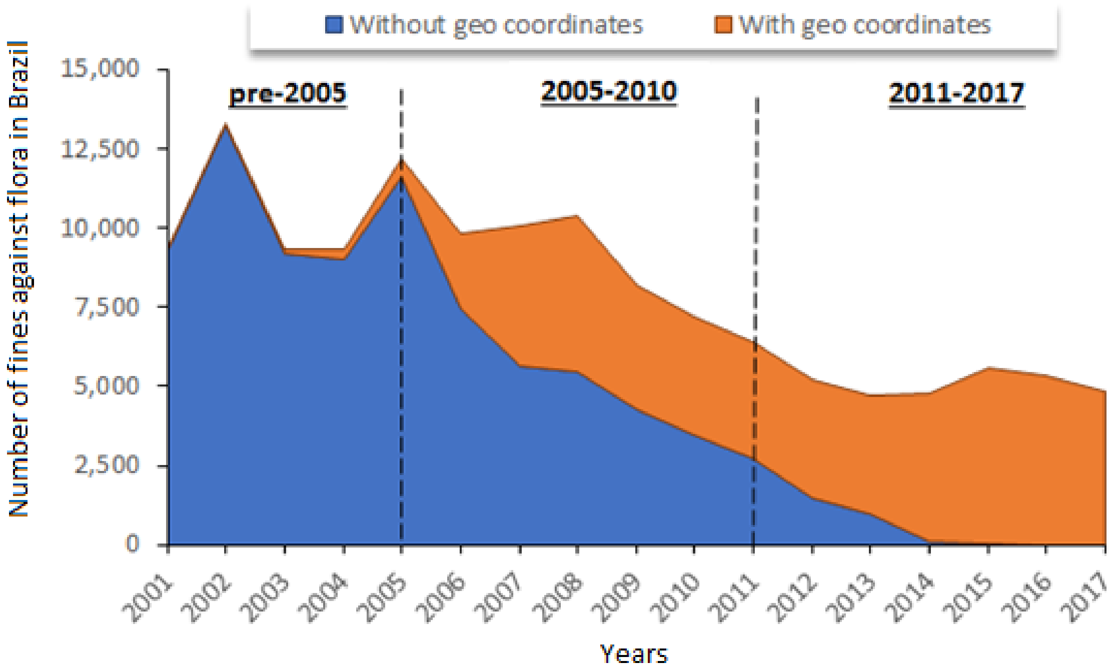

Figure S1 – Number of fines against flora in Brazil

Sources: 28, 29

Another important policy change was the Decree 6321/2007 that prevented landowners who illegally deforested to obtain subsidized loans from public banks, thus creating, for the first time, economic sanctions. The Decree required landowners who to regularize their situation, creating, for the first time, economic sanctions – restricting access to financing at subsidized interest rates from public banks. Finally, under Marina Silva's administration at the Environment Ministry, protected areas increased from 57 to 103 million hectares between 2003 and 2008, acting as a barrier against the expansion of the agricultural frontier[26].

Period 2011-Present: Stagnation in environmental governance (2011-12) political/economic crisis (2013-18) and growing deforestation (2013-17)

In this period, many of the deforestation reduction policies were maintained or marginally improved. At same time the number of law enforcement personnel at the federal level decreased and the creation of new protected areas as a barrier to deforestation was largely abandoned (see Figures below). However, the main change observed in this period was the emergence of a political crisis that incentivized illegal deforestation.

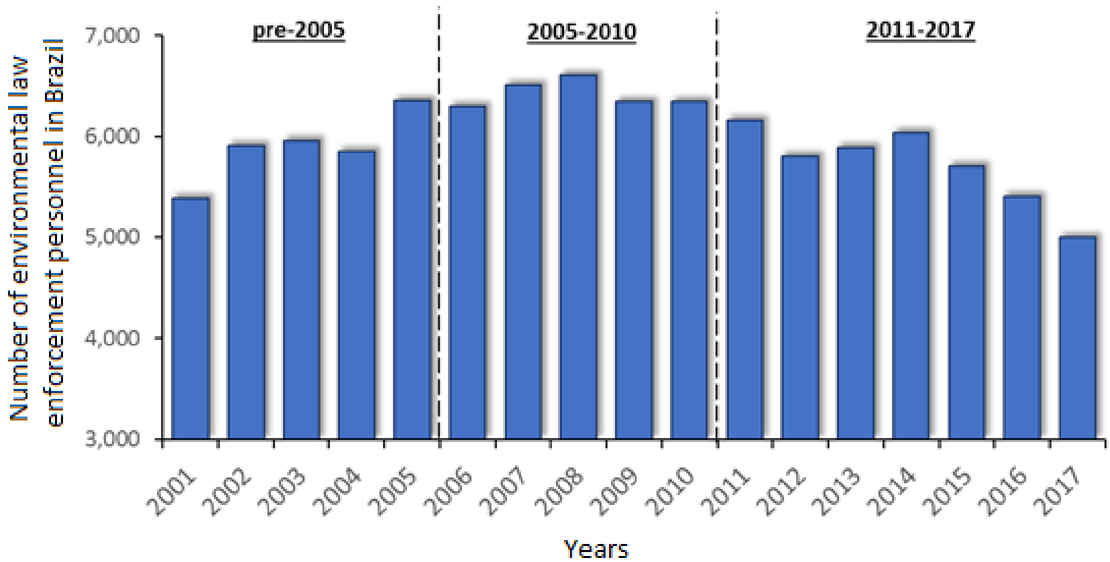

Figure S2 – Number of environmental law enforcement personnel in Brazil

Sources: 28, 29

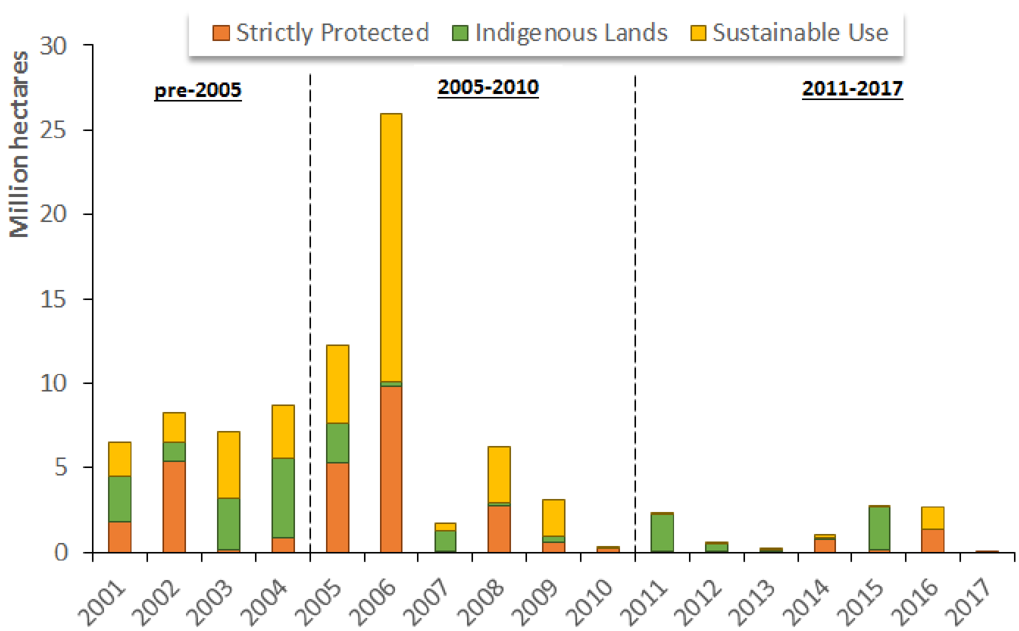

Figure S3 – Creation of new Protected Areas in Brazil

Sources: 28, 29

This change in governance can be explained by two main factors. First, an expressive growth of the agribusiness lobby stands out in the elected legislature in the period. The rural caucus at Congress went from 116 Congress members in the previous legislature to 142 in 2011-2014 and 207 in 2015-2018. This growth was associated with an improvement in their organizational robustness, leading to an offensive on environmental legislation, which succeeded in the Approval of the New Forest Code in 2012. The new Code gave a clear sign in favor of deforestation by the annulment of a large part of the fines accumulated by landowners with illegally-deforested areas.

Second, the weakening of environmental governance was also a consequence of a gradual loss of importance of climate/Amazon issue in Brazilian society, as a deep political and economic crisis settled in. In June 2013, there were massive anti-government mobilizations in favor of increasing the quality of transportation, education and health and denouncing the corruption generated in the construction of the stadiums for the 2014 Football World Championship. Some more insightful analysts had already detected that there was a latent malaise in society behind the apparent lull and satisfaction, but no one predicted the scale and intensity of the social and political contestation that took place in the country at that time. President Dilma Rousseff's approval rate fell from 66 percent to 31 percent between end-May and end-June 2013. By December 2013 it recovered to 39 percent, but the mood had irreversibly shifted. The political crisis widened and deepened with increasing polarization. The global commodities super-boom (2004-2013), which had strongly favored the Brazilian economy ended in 2013, worsening the already stressed fiscal situation. During the election year of 2014 the government extraordinarily increased public spending (with a major negative impact on the fiscal situation) to contain social dissatisfaction and recover the approval rates needed for re-election. Dilma Rousseff was reelected in 2014 in a strongly polarized and ugly fought election by a small margin of 3 percent in the second round.

The trend observed since 2013 was intensified after the 2014 elections. In the 2015-18 elected Congress, the agribusiness lobby again increased sharply from 142 to 207 members, representing 38 percent of congress members, which implied in a large gap in relation to the weight of agribusiness in the economy (approximately 20 percent). Faced with the country's deep fiscal imbalance, president Rousseff decided to start her second government with a fiscal adjustment that was the opposite of the promises of the election campaign. Her approval rates dropped dramatically from 50 percent in November 2014 to 15 percent in March 2015.

In 2015, GDP shrank by 3.7 percent and inflation almost doubled. In 2016, GDP fell again by 3.5 percent. Unemployment rates grew from 6 percent to 12 percent in 2014-16. In 2014-16 the anticorruption investigations carried out by the Federal Public Prosecutor and the Federal Police involved a large part of the political class and large national state-owned and private companies. Very powerful entrepreneurs and politicians were convicted and went to prison. In light of these events, sectors of the opposition began the path for the impeachment of the President.

In May 2016 the impeachment of President Rousseff was approved. The leader of the impeachment coalition, Vice-President Michel Temer, from the PMDB Party, who had formed a close alliance with the Workers Party for 13 years, took over the presidency and appointed a new cabinet, further increasing the weight of the agribusiness lobby in the executive power. The new economic policy was able to stave off the economic downturn, but it is unfriendly to climate, social and environmental issues.

In 2017, the Public Prosecutor charged president Temer himself twice for corruption crimes. Because of that, President Temer had to bargain votes from Congress members against his impeachment. In the bargaining process, several drawbacks in environmental policy took place throughout 2017. For instance, President Temer has proposed legislative projects and signed provisionary acts and decrees that lowered environmental licensing requirements, suspended the ratification of indigenous lands, reduced the size of protected areas in the Amazon and facilitated land grabbers to obtain the deeds of illegally deforested areas as large as 2,500 ha per farm in the Amazon rainforest. While some of those decrees were later cancelled under national and international outcry, they send a clear signal to that the political climate was favorable to illegal deforesters.

The political crisis gained force: by January 2018, the low approval rates of president Temer (6 percent) and Congress (8 percent) were without precedent in the Brazilian democratic history. Most observers of the Brazilian reality agree that there is widespread indignation and rage among people against public authorities in all levels of government. Adding to the malaise, public security reached extreme levels of deterioration, undermining the rule of law in many regions of the country, particularly in the Amazon where the control of deforestation requires strong law enforcement.

The economic, political and moral crises continually drove public attention away from climate/environmental issues. That, in addition to an increased representation of the agribusiness political forces from which an unpopular president draws a large share of his political support, led to a dramatic increase in the rate of deforestation in the 2015-17 period. The general elections for President, Congress and State Governors, to be held in October 2018, will be decisive for the overcoming (or not) of the Brazilian political crisis, in general, and for the course of environmental governance, particularly.

Finally, the three periods show that, on the one hand, law enforcement agencies can act strongly to contain deforestation (command-and-control agencies); on the other hand, the signals sent by the Government and other actors may directly or indirectly incentivize economic agents to increase deforestation pressure, thus countering the effect of these policies. Based on this, this study elaborated three scenarios:

- **Weak environmental governance (WEG)**: this scenario assumes the abandonment of current deforestation control policies, as well as a strong political support for predatory agricultural practices. In practice, by 2025 this scenario represents the reversal of the governance put in place in the middle 2000s. While unlikely, this represents the worst-case scenario in the study and should be understood as a complete reversal of environmental governance in Brazil, with severe impacts on deforestation rates, which potentially return to pre-2005 levels.
- **Intermediate environmental governance (IEG)**: this scenario assumes the maintenance of current deforestation control policies, while, contradictorily, considering growing political support for predatory agricultural practices. In this scenario, the efforts to reduce deforestation through existing command-and-control policies are overpowered by political forces associated with the rural caucus. This scenario also considers that the number of law-enforcement personnel in command-and-control agencies will continue to decrease, following the current trend, which is accrued by the freezing of real Federal budget expenses until 2036, established by constitutional amendment n°55/2016. This scenario also considers the legal support to land grabbing practices, the creation of fewer protected areas and the downgrading, downsizing and degazettement of key protected areas (measures which have been approved as bargaining chips during the ongoing political crisis). Therefore, IEG represents the business-as-usual scenario in Brazil, according to which the increasing deforestation trend observed in the Amazon since 2013 is extended until 2030.
- **Strong environmental governance (SEG)**: this scenario assumes the expansion of current deforestation control policies and full political support for an environmental agenda in the country. This scenario considers the increase in dedicated personnel in command-and-control

agencies and the combination of command-and-control actions with economic incentives for forest conservation. In addition, political leaders are assumed to show commitment to an environmental agenda and to reverse recent pro-deforestation legislation.

From these environmental governance scenarios, we estimated the associated land-use scenarios in a spatially-explicit land-use model, and the derived CO_2 emissions. Then, by running an integrated assessment model, we estimated the level of effort and the investment costs for other economic sectors to compensate for higher emissions from deforestation, if Brazil is to meet its commitment under the Paris Agreement to keep average surface temperature increase to “below 2°C” by 2100. To do so, we initially describe how the total Brazil CO_2 budget was established by Integrated Assessment Models (IAMs), assuming an optimal global least-cost effort to curb emissions to reach a “below 2°C” world. Then, we model the impacts of lower levels of environmental governance on land-use change (basically deforestation) and land-use CO_2 emissions. This expected increase in CO_2 emissions from deforestation reduces the remaining budget for the other economic sectors. In other words, the cumulative emissions from deforestation from 2010 to 2030 were subtracted from the total CO_2 budget allocated to Brazil by global IAMs. This provided the remaining budget for the rest of the Brazilian economy through 2050, compatible with a global scenario “below 2°C”. Then, we model the optimization of Brazil’s energy system (including industrial process emissions and solid wastes) constrained by this remaining CO_2 budget.

Total CO_2 budget for Brazil

The total CO_2 budget for Brazil used in this paper derived from the results of different global IAMs and international studies. These IAMs were applied in an international collective modelling effort called CD-Links (www.cdlinks.org). The following table details the Brazilian CO_2 budget in a 2^{o}C world, according to the results of these models, as well as other studies in the literature. The budget estimated from IAMs is the cumulative amount of CO_2 Brazil would emit in a least-cost, worldwide effort to keep global average temperature increase “below 2^{o}C” by 2100 with a likely chance (67-100% probability), assuming an optimal (least-cost) worldwide mitigation strategy. Other budget allocation criteria, including fairness, historic responsibility, grandfathering, per capita conversion, among others, are used in other international studies [18].

The values for the Brazilian CO_2 budget from 2010 to 2050 are presented in Table S1. It is important to notice that we have depicted only the budget for the 2010 to 2050 period, which is the time horizon for both models used in this study. These values are in line with each IAMs cumulative CO_2 budget up to 2100.

Table S1 – Literature values for the Brazilian CO_2 budget from 2010 to 2050

Period	Budget Gt CO_2	Probability < 2°C	How was budget determined?	Reference
2010-2050	21.0	67%	Allocation (per-capita)	[15]
2014-2050	18.0	RCP2.6	Allocation (C&C)	[16]
2010-2050	16.0	67%	PRIMAP model (min)	[17]
2010-2050	41.0	67%	PRIMAP model (max)	
2010-2050	19.8	n/a	Allocation TISS-DSF ScenA	[18]
2010-2050	21.1	n/a	Allocation TISS-DSF ScenA	
2010-2050	29.6	n/a	Allocation TISS-DSF ScenA	
2010-2050	41.4	n/a	Allocation TISS-DSF ScenA	
2010-2050	22.0	n/a	Allocation WWF-Ecofys CDC	
2010-2050	25.0	n/a	Allocation WWF-Ecofys GDR	
2010-2050	26.0	n/a	Allocation WWF-Ecofys C&C	
2010-2050	23.0	n/a	Allocation IEA (WEO2013)	
2010-2050	41.3	67%	Allocation (population)	[19]
2010-2050	4.7	67%	AIM/CGE - INDC 1000	[20]
2010-2050	0.5	67%	AIM/CGE - NPi 1000	
2010-2050	16.0	67%	COPPE-COFFEE 1.0 - INDC 1000	
2010-2050	23.6	67%	COPPE-COFFEE 1.0 - NPi 1000	
2010-2050	7.5	67%	DNE21+ V.14 - INDC 1000	
2010-2050	13.1	67%	DNE21+ V.14 - NPi 1000	
2010-2050	37.9	67%	IMAGE 3.0 - INDC 1000	
2010-2050	37.5	67%	IMAGE 3.0 - INDC 1000	
2010-2050	37.6	67%	IMAGE 3.0 - NPi 1000	
2010-2050	**23.8**	**-**	**Average value from literature**	

For this study, we have adopted the rounded average of the results of the literature, which equals to, approximately, 24.0 Gt CO_2, from 2010 to 2050. We recognize that there is a spread of values for the CO_2 budget allocated to Brazil in a "below 2°C" world. This uncertainty is discussed in the section "Limitation of the Study and Sensitivity Analyses", where a sensitivity analysis was performed to a higher and a lower CO_2 budget.

The budget used here relates to CO_2 only. The emissions of non-CO_2 GHG may be relevant in some regions, such as Brazil. However, CO_2 is the major GHG nationally and globally and IAM assessments do not always consider non-CO_2 gases due to their lower relevance and the methodological difficulties associated with GHG life-spans, their global warming potential and life cycle. In fact, the literature on carbon budgets shows a very strong relationship between cumulative CO_2 emissions and temperature increase and radiative forcing[33]. In the case of the model runs used in this study, non-CO_2 gases were dealt with as explained in the following section. This will be further discussed in the section "Limitation of the Study and Sensitivity Analyses".

Modeling procedure

Given the deforestation pathways, established by the causal chain from politics to land, and their related CO_2 emissions, a significant share of the national budget for the energy system is already compromised. Table S2 presents the available budgets for the other sectors (including the energy system, industrial processes and residues) of the economy for each of the three deforestation scenarios.

Table S2 – Brazilian "below 2°C" world CO_2 budget for deforestation and other sectors according to scenario

Scenario	CO_2 Budget (2010-2050)	
	Deforestation	Other Sectors
Strong Environmental Governance (SEG)	9.6	14.4
Intermediate Environmental Governance (IEG)	16.3	7.7
Weak Environmental Governance (WEG)	23.1	0.9

Note: Other sectors include: energy-related emissions, industrial processes and residues.

The methodological approach used in this study allows for an emission overshoot at extremely high costs in order to quantify eventual infeasibilities in achieving the CO_2 budget.

Most policy-relevant carbon budget estimates take into account the influence of non-CO_2 forcers by considering consistent evolutions of CO_2 and non-CO_2 forcers from integrated scenarios. Therefore, to limit the emissions of non-CO_2 gases an emission cost was applied to those gases only. The methodology was based on using carbon prices aligned with the emission pathway for reaching the 2°C budget. Carbon price trajectories were taken from the integrated assessment literature. Figure S4 presents the literature review of carbon prices in 2050, indicating the mean, minimum, maximum and percentile values. Overall, 38 data points from the scientific literature [23, 34-35] were used.

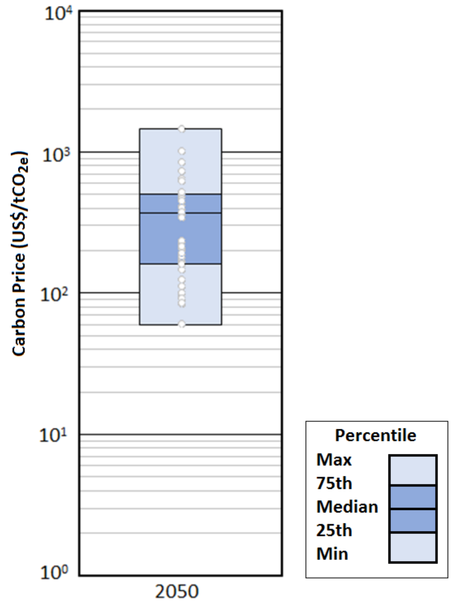

Figure S4 – Carbon price range, in 2050, for a "below 2°C" world
Sources: 16, 20, 21

Dealing with non-CO_2 sources in such a manner is especially important for assessing scenarios for Brazil, for two main reasons: almost half the GHG emissions in Brazil derives from methane, mostly from livestock, and nitrous oxide, from agriculture; given the potential role of bioenergy, for curbing CO_2 emissions, Brazil could easily intensify the use of energy crops for mitigating CO_2 emissions, whilst increasing N_2O emissions. Thus, the GHG emissions could actually increase and diverge from a 2°C pathway. Therefore, limiting non-CO_2 emissions even in a scenario with a CO_2-only budget is necessary, especially for the Brazilian case.

In this study we used GWP_{100}-AR5 to apply CO_{2e} prices to non-CO_2 gases. The chosen value for the price of non-CO_2 emissions was the median 2050 value of the values shown in Figure S4, namely \$370/tCO_{2e}. Non-CO_2 gases were priced by multiplying this CO_2 price by the GWP-AR5 conversion factor for each non-CO_2 gas and then applied as a constant from 2020 to 2050 (methane – CH_4 - GWP_{100} of 28; nitrous oxide – N_2O – GWP_{100} of 265). This means the mitigation costs of non- CO_2 gases were included in the objective function of the least-cost optimization model instead of by constrains, meaning that they affect the model´s choices by changing the cost of those commodities that cause non-CO_2 GHG emissions.

Land use modelling

OTIMIZAGRO is an upgraded version of SimAmazonia/SimBrasil[36-38]. OTIMIZAGRO is a nationwide, spatially-explicit model that simulates land use, land-use change, forestry, deforestation, regrowth, and associated carbon emissions under various scenarios of agricultural land demand and environmental policies for Brazil[21,39]. OTIMIZAGRO simulates nine annual crops (*i.e.* soy, sugarcane, corn, cotton, wheat, beans, rice, manioc, and tobacco), including single and double cropping; five perennial crops (i.e. Arabica coffee, Robusta coffee, oranges, bananas, and cocoa); and plantation forests. The model framework, developed using the Dinamica EGO platform (*6*), is structured in four spatial levels: (i) Brazil's biomes, (ii) IBGE micro-regions, (iii) Brazilian municipalities, and (iv) a raster grid with 25 ha spatial resolution.

Because there is no map at this spatial resolution with the above specific land-use classes available for the whole country, the initial land-use map is a composite of several spatial data sources. Current land use map for Brazil, as of 2012 (Figure S5), is a composite of datasets including for the Amazon the land cover maps from PRODES [14] and land use maps from TerraClass[41], for the Atlantic forest the SOS Mata Atlântica land cover map[42] and for the other biomes the land cover maps from PROBIO [43]. Specifically for the Pampa, the riparian vegetation is added using data from Hansen et al.[44]. To this land use composite, we include the urban areas by overlaying the IBGE census tract classified as such[45]. In addition, large mechanized croplands, such as soy and corn, come from the maps provided by INPE[46]. To this composite map, OTIMIZAGRO spatially allocates the remainder annual and perennial crops over the converted land by using maps of crop aptitude and profitability [21], which were calculated using regional selling prices, production and transportation costs[47,48]. OTIMIZAGRO also takes into account the respective municipal areas at the initial year[49].

Future demand for crops, and deforestation and regrowth rates are exogenous to the model. When the available land in a given micro-region (or other specified spatial unit) is insufficient to meet the specified land allocation, OTIMIZAGRO reallocates the distribution of remaining land demands to neighboring regions, creating a spillover effect. The probability of deforestation is a function of spatial determinants, such as distances to roads and previously deforested areas[36].

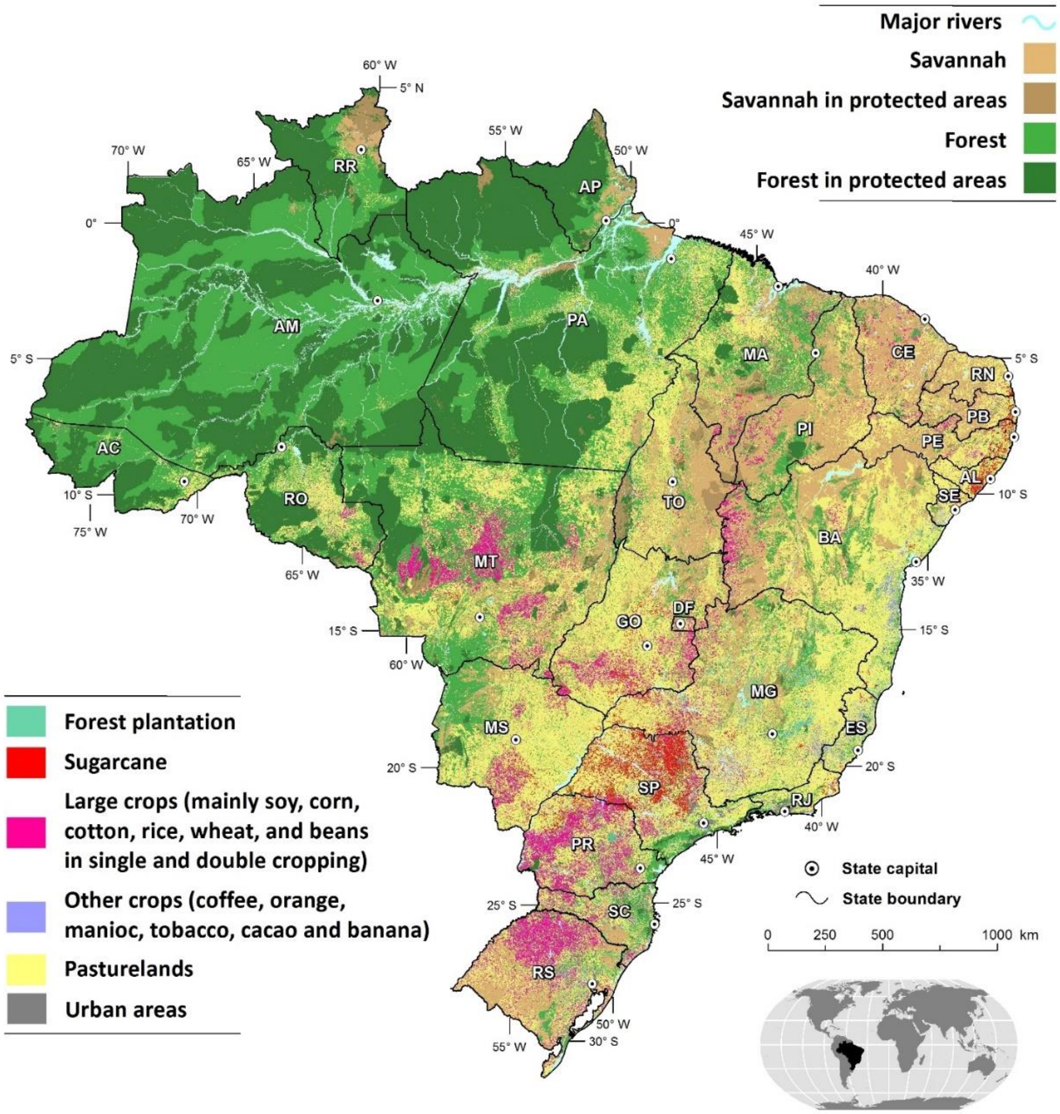

Figure S5 – Land use in Brazil as of 2012

Deforestation rates of 2010-2016 are the annual records for the Amazon[14] and Cerrado[50]. Projected annual deforestation rates for 2017-2030 were defined by environmental governance that considered a set of governmental policies as well as the broader political context. These scenarios consist of:

- *Weak environmental governance (WEG)* scenario projects future annual rates based on the reversal of the deforestation reductions observed between 2002 and 2008 for the Amazon[14], limited to 2004 peak of 27,772 km^2. Likewise, for the Cerrado biome the model projects annual deforestation rates based on reversal of the reduction trend observed between 2004 and 2014[50] limited to 2004 peak level (18,517 km2). For the other biomes, the model uses the 2002-2010 annual averages[51], except for Atlantic Forest where the rates were set to zero because of Atlantic Forest Law[52].
- *Intermediate environmental governance (IEG)* scenario projects future annual rates based on the deforestation trend observed between 2012 and 2016 for the Amazon[14], limited to 2004 peak of 27,772 km^2. For the Cerrado biome, the model projects annual deforestation rates based on the

reversal of the reduction trend observed between 2009 and 2011[50] limited to 2004 peak level (18,517 km^2). For the other biomes, the model uses the 2002-2010 annual averages[51], except for Atlantic Forest where the rates were set to zero because of Atlantic Forest Law[52]. Here deforestation rates are also increasing, albeit, more slowly than in WEG.

- *Strong environmental governance (SEG)* scenario projects rates for the Amazon to reach 3,920 km^2 and Cerrado to reach 3,794 by 2030 in compliance with National Plan on Climate Change[53]. For the other biomes, the model uses the 2002-2010 annual averages[51], except for Atlantic Forest where the rates were set to zero because of Atlantic Forest Law[52]. Deforestation in the *SEG* scenario is constrained to areas of Forest Code surplus to allow only legal deforestation[28].

In order to account for net emissions from land-use, land-use change and forestry (LULUCF), the model focused on the gross emissions from deforestation and removals from native vegetation regeneration. According to Brazil's Third National Communication (TCN, acronym in Portuguese) deforestation corresponds to 86 percent of gross emissions from LULUCF[51]. The land-use model accounts for deforestation emissions by laying the biomass map of native vegetation over the simulated land use maps.

The SEG scenario includes removals from restoration of native vegetation (methodology explained bellow) associated with the full implementation of the Forest Code, which does not take place in the IEG and WEG scenarios. In this case, forest regrowth would cumulatively remove 0.61 Gt CO_2 by 2030 and 2.2 Gt CO_2 by 2050.

According to the TCN, other sources of removal consist of sequestration by forests in protected areas and expansion of forest plantation[51]. In all scenarios, the extent of protected areas and expansion of forest plantations are the same, and as such their related removals do not differ. See discussion on the uncertainties of these and other carbon sinks in section "Limitation of the Study and Sensitivity Analyses" of this Supplementary Material.

This study uses as our database for emission calculations Brazil's greenhouse gas inventory of the Third National Communication (TCN) submitted to the United Nations Framework Convention on Climate Change (UNFCCC)[51]. The choice of using the TCN allows to compare our results with Brazil's current level of emissions as well as with its NDC's target using the same framework. As a result, this choice facilitates the communication and comparability of the results of this study to policy makers and stakeholders not only in Brazil, but also amid the international climate policy arena.

It must also be stressed that TCN provides sufficient technical quality and information to support a comprehensive countrywide analysis and was developed based on the Intergovernmental Panel on Climate Change (IPCC) guidelines. As the national Greenhouse Gas (GHG) emission inventory, TCN is the most comprehensive database available for Brazil.

The TCN biomass map (Figure S6) was elaborated by using the forest inventory data of the RadamBrasil Project for the Amazon and data from literature for the other biomes. The biomass map accounts for native vegetation aboveground and belowground, live biomass, deadwood, and litter for specific vegetation types across the country. This represents large improvements in relation to the map of the Second National Communication (SCN, acronym in Portuguese)[54]. In summary, these advances are the following:

- More rigorous selection of the RadamBrasil Project data plots;

- New allometric equations for the above-ground biomass from review and comparison with forest inventories[55], which include: Amazon Forest Inventory Network (RAINFOR), Tropical Ecology Assessment and Monitoring (TEAM) and Amazon Tree Diversity Network, Biodiversity Research Program (PPBio);
- Improvement in the spatial interpolation of the RadamBrasil samples to produce a more continuous map in comparison to the one of the SCN; and
- Review and update of biomass values by phytophysiognomies in Atlantic Forest, Cerrado, Caatinga, Pampa and Pantanal.

Carbon stocks of the replacement land uses, pasture and crop correspond to 7.57 tC/ha and 5.00 tC/ha, respectively.

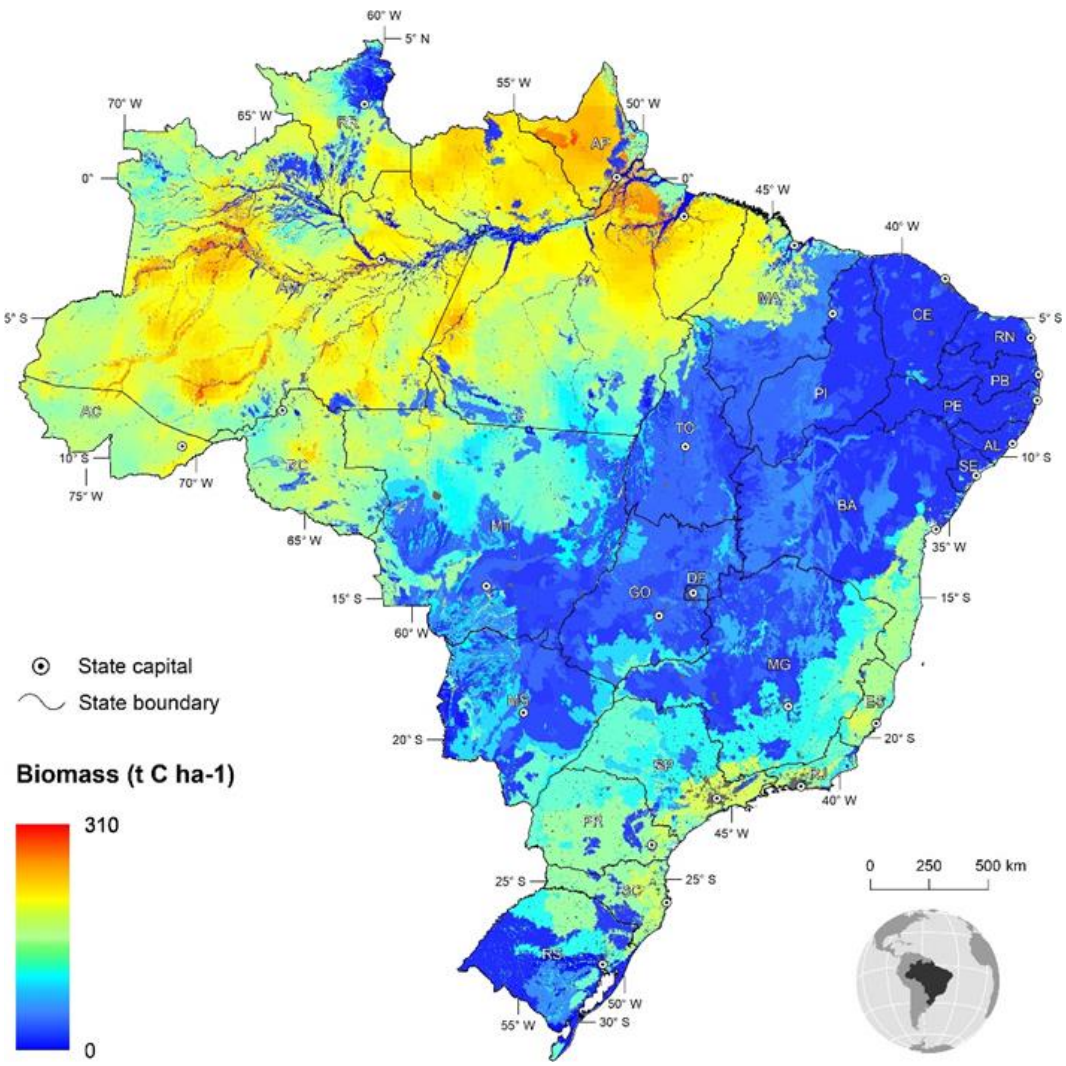

Figure S6 – Above and below ground biomass

The model accounts for carbon removals by regeneration of native vegetation using the yearly removal factors of Table S3 and considering an upper limit of 44 percent of the corresponding original biomass also following the specifications of the TCN[51]. This limit represents average values for primary and secondary forest identified in the literature[56-59].

Table S3 – Carbon Removal factors for vegetation regrowth for Brazil's biomes land use transitions

Land use transitions	*(tC/ha/year)* Amazon	*Cerrado*	*Atlantic Forest*	*Caatinga*	*Pampas*	*Pantanal*	*Reference*
Grasslands or other land use to Grasslands	*0.52*	*0.52*	*0.52*	*0.52*	*0.52*	*0.52*	*60-61*
Forest to Forest	*4.96*	*1.72*	*5.35*	*0.6*	*1.76*	*2.77*	*57-59, 61-69*
Pastureland to Forest	*2.85*	*2.85*	*2.85*	*2.85*	*2.85*	*2.85*	*61,70*
Cropland to Forest	*4.73*	*4.73*	*4.73*	*4.73*	*4.73*	*4.73*	*57,61*
Others to Forest	*0.59*	*0.59*	*0.59*	*0.59*	*0.59*	*0.59*	*61, 71*

Energy-system modelling

Integrated assessment models (IAMs) map the interactions between socioeconomic systems and energy and environmental processes and are used to develop emission scenarios, estimating the costs and benefits of mitigation policies and the economic impacts of climate change. IAMs experiences combine models from different areas of knowledge. A detailed representation of the energy system is necessary - considering conventional and alternative energy uses. The same applies for land use – considering agriculture, livestock and forests in different ecosystems–, and the economic system, considering sectoral elasticities and productivities, even if using a simplified approach.

An IAM called Brazilian Land Use and Energy System (BLUES) simulated the evolution of the Brazilian energy, industrial and waste sectors and their emissions under this budget constraint through 2050 (for further details on model documentation and updated information, please refer to http://themasites.pbl.nl/models/advance/index.php/Reference_card_-_BLUES).

The BLUES model is a perfect-foresight, least-cost optimization model for Brazil, which was built on the MESSAGE (Model for Energy Supply Strategy Alternatives and Their General Environmental Impacts) model generator platform. MESSAGE is an optimization software in linear programming for energy systems developed by IIASA (International Institute for Applied System Analysis)[72,73]. In simple terms, the model is designed to simulate the competition between technologies and energy sources to meet the demand for energy services (that are exogenous to the model, including lighting, heating/cooling requirements, mechanical energy, mobility, among others), with the objective of minimizing the total cost of the system. There are several studies in the literature using MESSAGE that analyze energy mix scenarios for medium and long-term public policies in several countries[74-78].

The platform is designed to develop and evaluate alternative strategies for energy supply, in line with restrictions such as limits for investments, fuel availability and prices, environmental regulations, market penetration rates for new technologies, among others. In order to make this possible, the analyst must build the energy flows that describe the energy system from the energy resources level, through primary, secondary, final and auxiliary levels, all the way to end or useful consumption[78]. Throughout these energy levels, conversion technologies must be specified with the appropriate parameters and constraints such as installed capacity, potential availability, capacity factors and efficiencies, investment and operation & maintenance costs, variable and fixed life span and expansion restrictions.

The costs and performance characteristics (efficiencies, capacity factors, environmental indicators, etc.) of technological alternatives are amongst the most important input data for the model. These values can change throughout the time scale of the model and are arguably a very sensitive input to the model. All these data are then used to form energy vector costs and promote competition between alternative technologies and resources for meeting the various energy demands. Each primary energy source can be divided into an optional number of classes, taking into account the extraction costs, quality of the sources and location of deposits. This stratification allows to represent in the model the non-linear relationships between extraction costs and the amount of available resources. Then these primary energy sources are transformed, directly or indirectly, into secondary and final energy sources and, finally, into energy services to meet the demand. The energy demands can be divided regionally and, in certain cases, as for electricity, it is possible to represent a system load curve.

All restrictions on, for instance, the availability of resources, availability of infrastructure for transmission and distribution of energy conversion and possible environmental constraints need to be met within the scenarios[79]. Environmental aspects can be evaluated by accounting and, if necessary, limiting emissions of pollutants from various technologies at various levels along the energy production and consumption chains. This allows the model to assess the impact of environmental regulations on the development of energy systems. The inclusion of such environmental constraints, for example for GHG emissions, is of fundamental importance to carry out this research.

The total cost of the system includes the investment costs, operating costs and additional costs, such as "penalties" for certain alternatives, such as environmental and social costs. The total value is calculated by discounting all the costs that occur at later points on a per year basis for the case study, and the minimization of the sum of the discounted total costs is used to find the optimal solution. This approach allows an assessment of the long-term role of energy supply options in competitive conditions[78].

The basic equation solved by the MESSAGE model is expressed below.

$$\min Z = \sum_{t=1}^{k}\left[\sum_{j=1}^{m}\frac{(R_j * CE_j)_t}{(1+d)^{(k-t)}} + \sum_{i=1}^{n}\frac{(P_i * CI_i)_t + (E_i * COM_i)_t}{(1+d)^{(k-t)}}\right] \qquad (1)$$

Subject to

$$P_i^{min} \le P^i \le P_i^{max} \qquad (i = 1, \dots, n) \qquad (2)$$

$$E_i^{min} \le E^i \le E_i^{max} \qquad (i = 1, \dots, n) \qquad (3)$$

$$\sum_{t=1}^{k} R_{j,t} \le R_j^{tot} \qquad (j = 1, \dots, m) \qquad (4)$$

$$\sum_{t=1}^{n} E_{i,l,t} \leq D_{l,t} \quad (l = 1, \dots, a)(t = 1, \dots, k) \qquad (5)$$

$$E_i \leq P_i * FC_i \qquad (i = 1, \dots, n) \qquad (6)$$

Where *k* is the period of analysis; *m* the quantity of available resources; *n* the total number of available technologies; *d* is the discount rate; *R* is energy extraction of resource *j* in year *k*; *CE* the unit cost of extraction of resource j in year k; *P* is installed capacity of technology *i* in year *k*; *CI* is the unit investment cost of technology *i* in year *k*; *E* is the energy produced by technology *i* in year *k*; *COM* the cost of operation and management of technology *i* in year *k*; *D* is the final demand for energy carrier *l* in year *k*; *a* the quantity of energy carriers used; and *FC* is the capacity factor of technology *i* in year *k*.

In recent years, the Brazilian version of MESSAGE has been substantially updated and applied to assess issues relevant to the national reality[80-82]. More recently, the model has been completely reconfigured to ensure a better detailing of both the regional breakdown as well as endogenous energy efficiency and GHG mitigation options in the end-use sectors. It has also been expanded to include the land-use sector, according to methodology proposed in Rochedo[83]. As mentioned before, this new version was named BLUES. It is included in the category of IAMs that combine techno-economic and environmental variables to generate cost-optimal solutions. The model minimizes costs of the entire energy system, including electricity generation, agriculture, industry, transport and the buildings sectors, subject to constraints that represent real-world restrictions to the full range of the variables in question. Such restrictions include, for example, the availability of resources, infrastructure, import possibilities, environmental restrictions and regulations, investment limits, availability and price of fuels, and market penetration rates for new technologies, among others. BLUES finds optimized mixes for all the considered systems as a whole, rather than evaluating sectorial optimal solutions. It includes CO_2, CH_4 and N_2O emissions associated with land use, agriculture and livestock, fugitive emissions, fuel combustion, industrial processes and waste treatment.

BLUES has six native regions, in which one is a main overarching region into which five sub-regions following the geopolitical division of Brazil are nested (Figure S7). BLUES optimizes the energy system between 2010 and 2050 in 5-year intervals. Each representative year is divided into 12 representative days (one for each month) made up of 24 representative hours. In other words, there are 12 load curves of 24 hours each, leading to a total of 288 time slices per year. Power generation must balance supply for every time slice. Intermittent sources are restricted to 25% of total power generation capacity[84], beyond which a fully dispatchable technology (for example open-cycle gas turbines) must be jointly deployed as a capacity reserve.

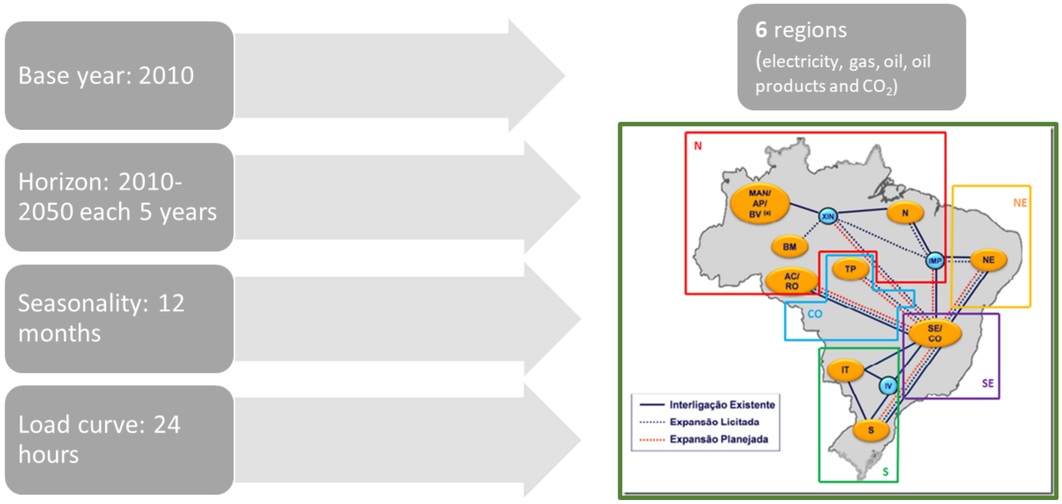

Figure S7 – Spatial and temporal resolution of the BLUES model.
Solid lines on the map represent existing interconnections; dashed lines represent limited of planned expansions

The energy system is represented in detail across energy transformation, transport and consumption sectors, with over 1500 technologies customized for each of its six native regions. The following paragraphs illustrate typical nodes in BLUES for the industry, transportation and buildings sectors, with examples of processes that transform the commodities available in each sector into final products. These figures exemplify how the model is structured to meet energy service demands, using different energy sources, processes or energy efficiency.

The industrial sector is broken up into eleven detailed sub-sectors including cement, ceramics, chemicals, food & beverages, iron & steel, metallurgy, mining, alloys, pulp & paper, textiles and a last aggregate of other industries. Figure S8 shows a typical node structure of the industrial sector with the available energy carriers.

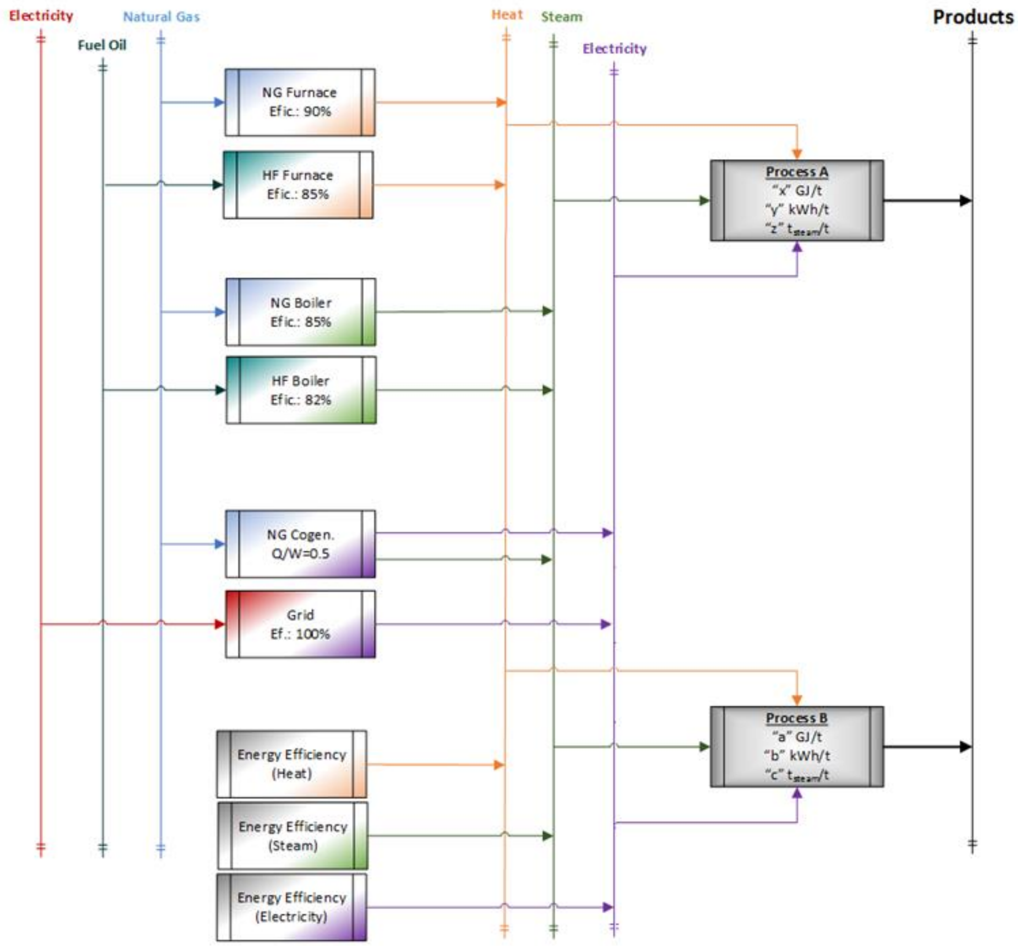

Figure S8 – Typical node structure in BLUES industry sector

The transportation sector is divided into passenger and freight transportation. Passenger transportation takes exogenous demand for transportation services (passenger-km – pkm) and allocates it to different transportation technologies based on costs and on modal splits from literature and auxiliary models. Passenger private transportation modes include light-duty-vehicles (LDVs), motorcycles, while passenger public transportation includes buses, micro-buses, subways (metro), rail, airplane and boats. LDVs can be powered by gasoline, ethanol, flex (ethanol and gasoline), hybrid, plug-in hybrid and battery electric vehicles. Motorcycles can be either fueled by gasoline, flex or electric. Buses can be powered by diesel, ethanol, biodiesel, and electricity. Boats can be powered by heavy fuel oil (bunker) or diesel. Figure S9 shows a typical node structure of the transportation sector with the available energy carriers and services.

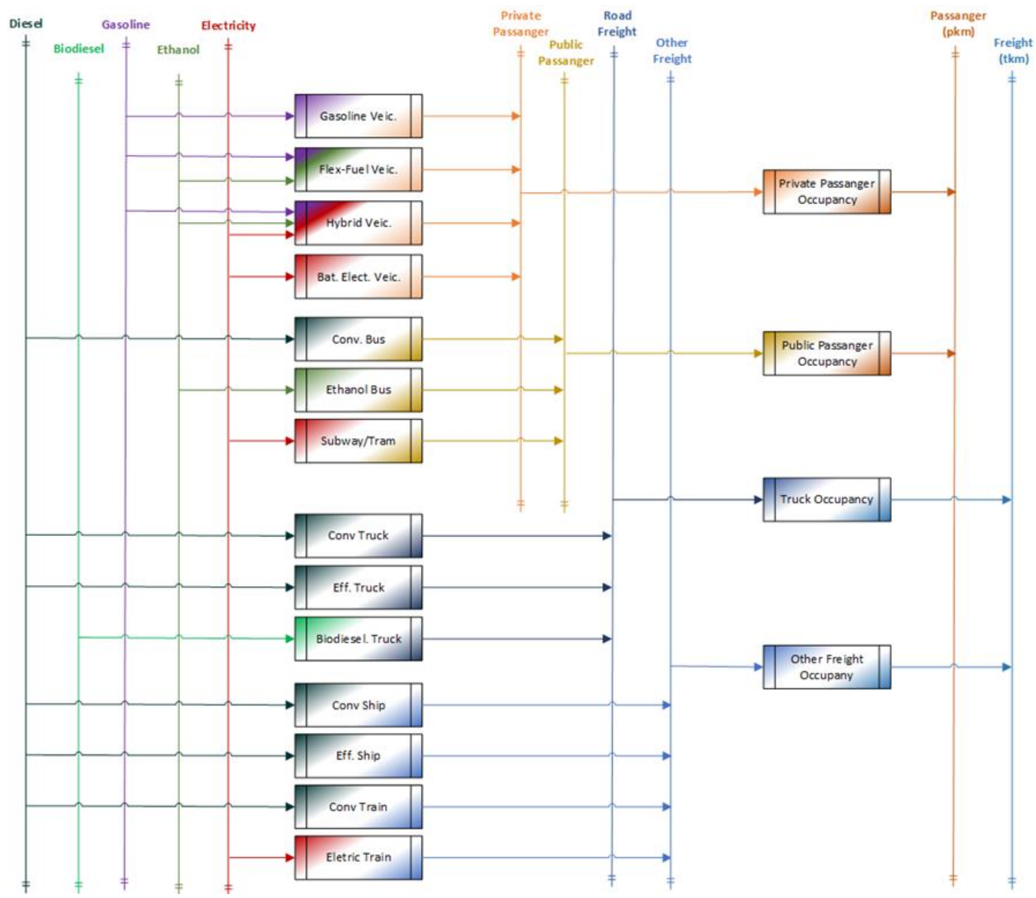

Figure S9 – Typical node structure in BLUES transportation sector

Freight transportation includes trucks, rail and ships to attend to an exogenous demand for transportation services (tonne-km – tkm). Trucks may use either diesel, biodiesel or a blend, while trains may use diesel or electricity. Ships use heavy fuel oil exclusively. Although hydrogen is an important future alternative for decarbonizing transportation, the scaling up of a hydrogen economy is not expected to be feasible in Brazil before 2050. Since BLUES does not (yet) include post-2050 periods, hydrogen is not implemented as a fuel alternative for the transportation sector.

The buildings sector is made up of the residential, commercial and public sectors. The end-uses considered are lighting, air conditioning, refrigeration, cooking, water heating and appliances. End-use technologies can use electricity, natural gas, liquefied petroleum gas (LPG), fuel oil, diesel, biomass or charcoal, depending on the end-use. A portfolio of technological alternatives for energy-use efficiency and demand reduction is available, which includes, for example, LED light bulbs, efficient appliances and distributed generation (rooftop photovoltaic and solar heaters). Figure S10 shows a typical node structure of the buildings sector with the available energy carriers and services.

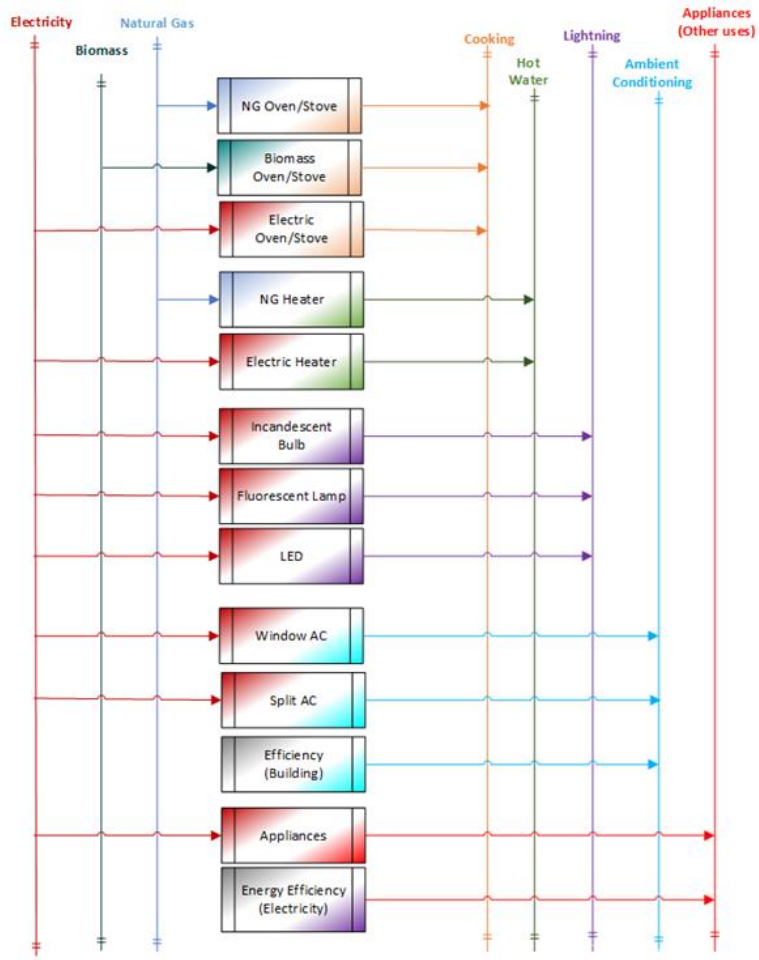

Figure S10 – Typical node structure in BLUES buildings sector

The representation of the land-use system includes forests, savannas, low- and high-capacity pastures, integrated livestock-cropland-forestry systems, cropland, double cropping, planted forests and protected areas. Cropland includes the major agricultural products in Brazil following the United Nations Food and Agriculture Organization (FAO) definitions for each category[85]: wheat, fruits, soybeans, maize, cereal, vegetables, roots, rice, pulses, oilseed, nuts, sugarcane, coffee, fiber, and grassy biomass. Woody biomass can come from Planted forests and forestry residue. Both agricultural and forestry residues may enter the biomass chain. Double-cropping is included for soy-maize and soy-wheat combinations.

Figure S11 shows the land use transitions modelled in BLUES. It must be noted that any unit area of land may undergo more than one transition in a single time step, so that all land use classes are interlinked. Costs are modelled individually for each transition and accrue as a unit area goes through consecutive land use transitions.

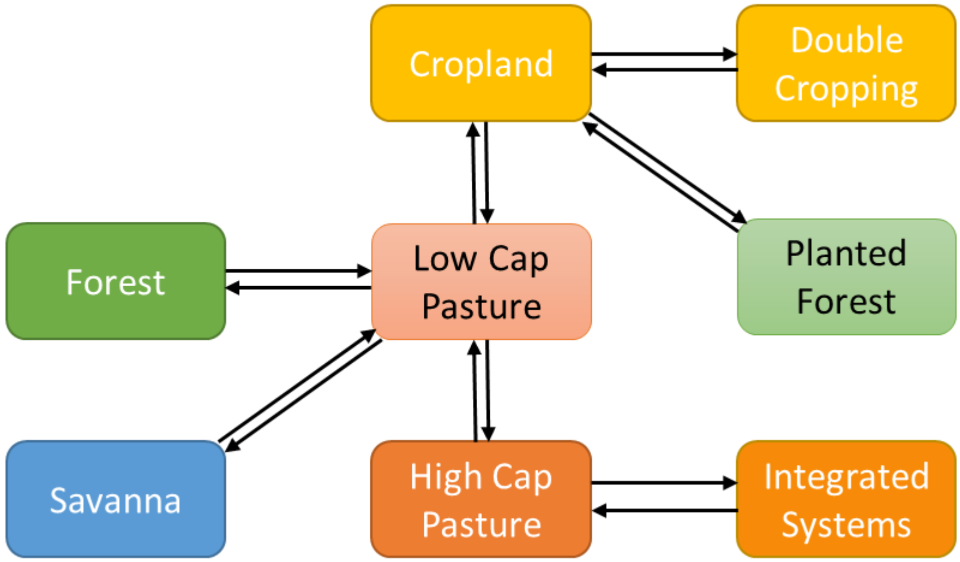

Figure S11 – Land use transitions modelled in BLUES

For the 2010-2030 period, the results from land use were provided by the detailed analysis of OTIMIZAGRO and simulated in the BLUES model, which optimized the energy system. Then, to be able to cope with the carbon budget through 2050, BLUES was free to model land-use transitions from 2031 to 2050. These land-use transitions were calibrated according to OTIMIZAGRO results.

In sum, BLUES has almost 28,000 technological nodes, of which roughly 8,000 are specific for the representation of the energy system and the additional 20,000 were developed for the representation of the land system. The optimization is made using the CPLEX solver, for almost 9,000 user-specified restrictions. Overall, the model presents over one million decision variables and represents a linear programming problem with over five hundred thousand rows and four hundred thousand columns.

S2. Supplementary Results

This section provides an analysis of the results obtained in this study. Initially, the results of the land use model are detailed, including projected maps for land-use change, the associated CO_2 emissions and a discussion about the remaining budget left for other economic sectors. Then, the results of the energy model are presented, including the energy sources projected for the Brazilian energy mix through 2050 in each scenario. Finally, this section presents the costs associated with each scenario.

Land use change results

Findings show that in 2030 total deforestation reaches 340,244 km^2 in the Amazon and 296,211 km^2 in the Cerrado. These estimates are 165% and 87% higher for the Amazon and Cerrado, respectively, when compared to the *SEG* scenario in the same year Accumulated emissions from deforestation and removals from restoration (only in the SEG scenario) reach 23.1 Gt CO_2, 16.3 Gt CO_2 and 9.6 Gt CO_2 in 2030, in the

WEG, IEG and SEG scenarios, respectively. These values were used in the BLUES model to run the total Brazilian CO_2 budget, as discussed in the "Supplementary Methods" section.

Nevertheless, we do recognize that the deforestation rate trends considered in our three scenarios could last through the mid-century (2050), should the Brazilian rural/mining caucus keep their political influence longer then considered possible here.

As mentioned before, to be conservative in our integrated assessment model BLUES, we have set 2030 as the final year of the policy induced land-use change trends, allowing the model to run freely after that. Actually, struggling to run the deforestation rates of the *IEG* scenario until 2050, BLUES was not able to find a feasible solution, meaning that it is not possible to keep these rates until 2050 and simultaneously cope with Brazil's CO_2 budget. By extension, the same is valid for the *WEG* scenario. Figure S12 and Figure S13 depict the deforestation maps of Brazil under the *WEG* (2030) and the *Extended WEG* (2050) scenarios, emphasizing biomes and areas at risk of deforestation.

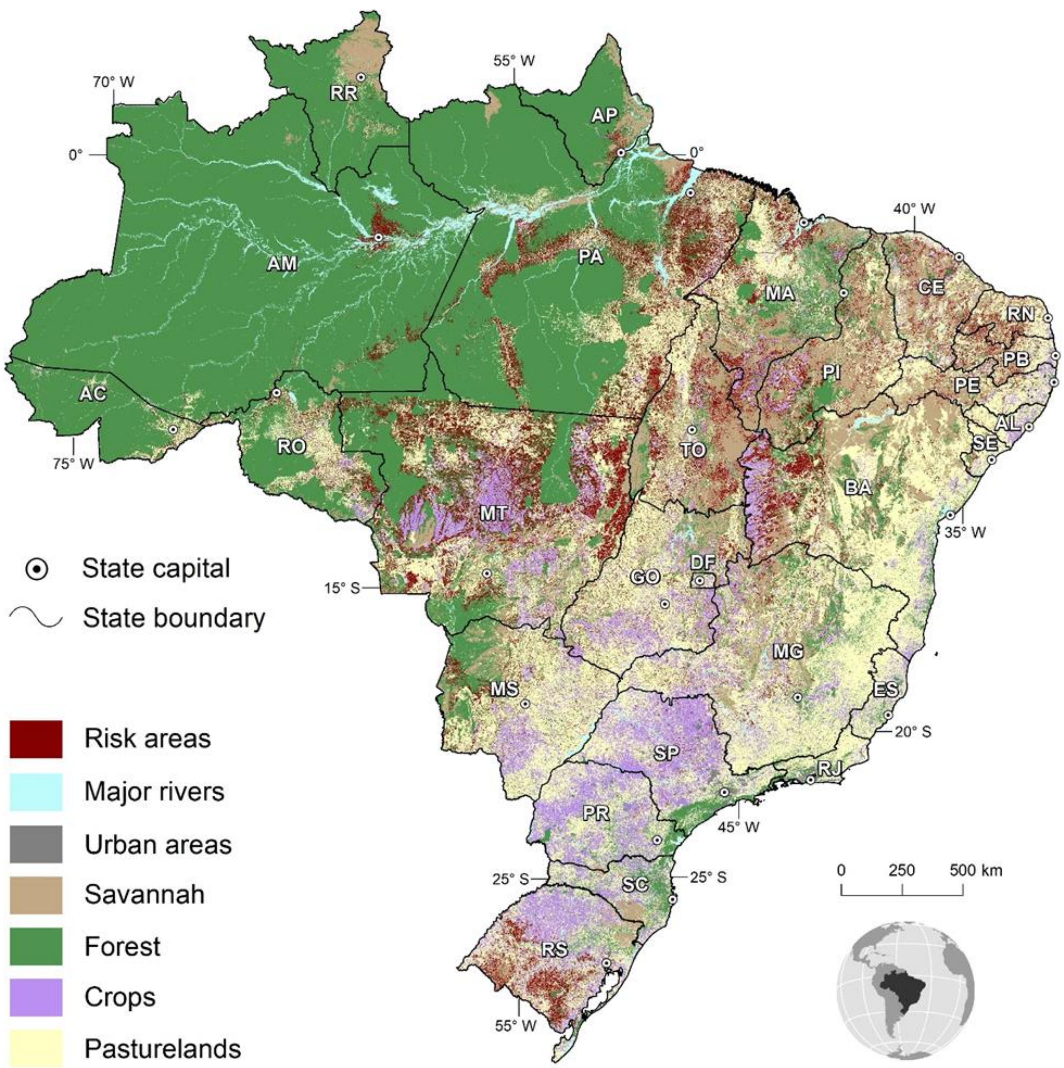

Figure S12 – Land-use change in 2030 in the WEG scenario

Note: Risk areas are those projected to be deforested in the respective scenario

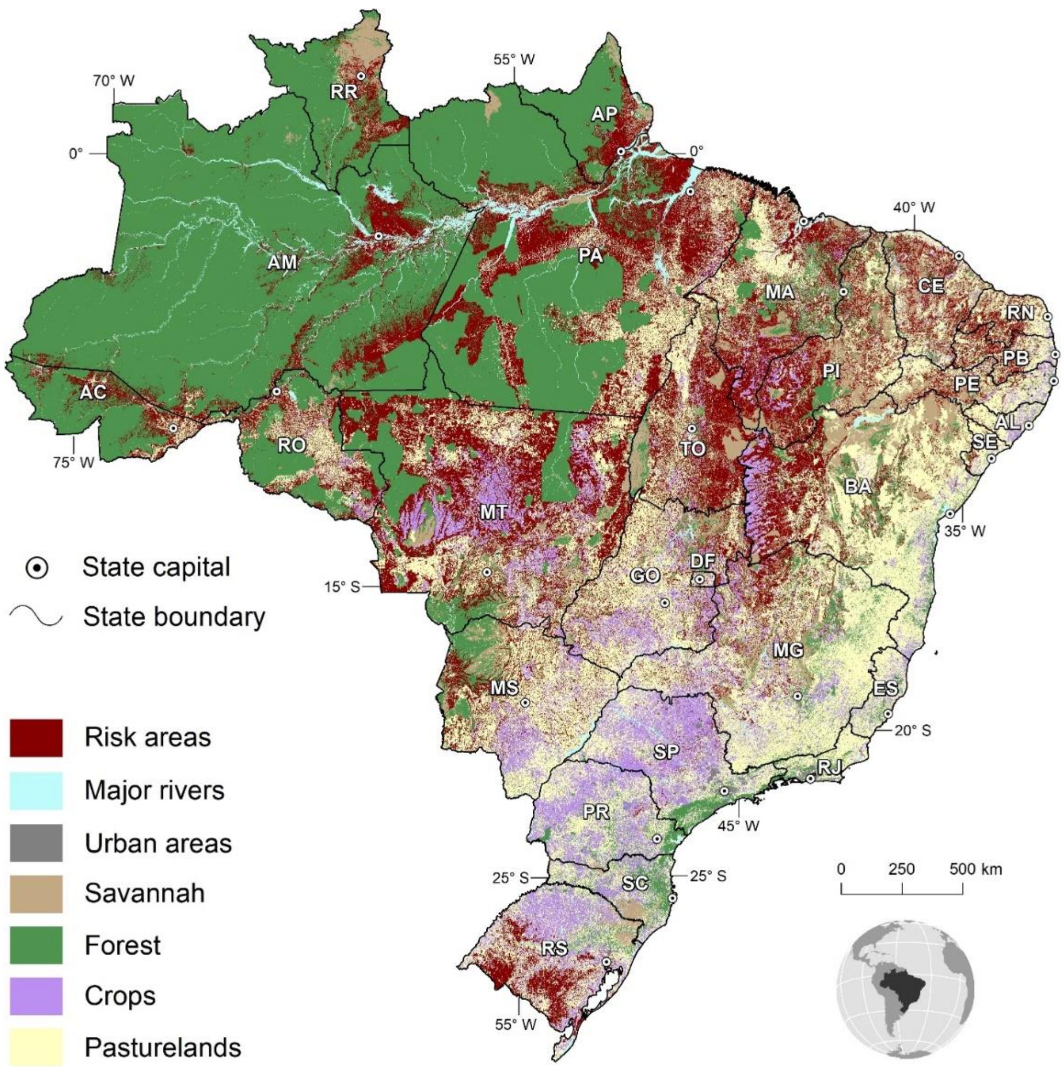

Figure S13 – Land-use change in 2050 in the Extended WEG scenario

Note: Risk areas are those projected to be deforested in the respective scenario

In this Supplementary Material we show the land use change associated with deforestation not only considering 2030 as the final year of policy-induced deforestation in the Amazon and Cerrado, but also going all the way to 2050 as the final year. These “extended” deforestation scenarios would lead to much higher cumulative CO_2 emissions than could be compensated by the other sectors of the economy (Figure S14).

For instance, in an *Extended IEG* scenario, deforestation (Amazonia plus Cerrado) would lead to the emission of 48.5 Gt CO_2 (almost doubling the budget allowed for the 2010-2050 period). In the *Extended WEG* scenario, accounting only for the Amazon, deforestation would lead to roughly the same annual result. In that case, the loss in the Amazon could sum 895,684 km^2, and in the Cerrado, 666,554 km^2 (Figure S13).

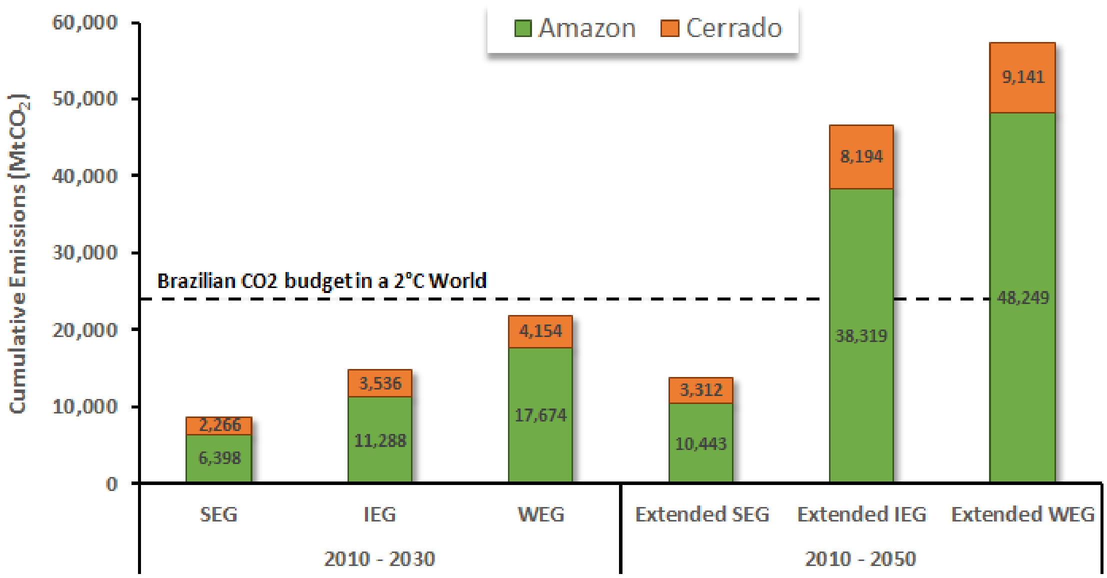

Figure S14 – Accumulated deforestation emission for the Amazon and Cerrado, highlighting the national budget (dashed line) and the difference between scenarios until 2030 (left) and extended scenarios until 2050 (right)

Energy-system results

This section explores the main results for the energy system in all three scenarios developed in this study. Figure S15 presents the CO_2 emission pathways for the energy system, industrial processes and residues. For the *SEG* scenario, the one with largest available share of the national budgets for the energy system, emissions drop steadily after 2020 and reaches about 100 Mt CO_2/year in 2050. In the *IEG* scenario, emissions drop more rapidly until 2040 and, despite a small increase up until 2050, it is consistent with the sectoral CO_2 budget.

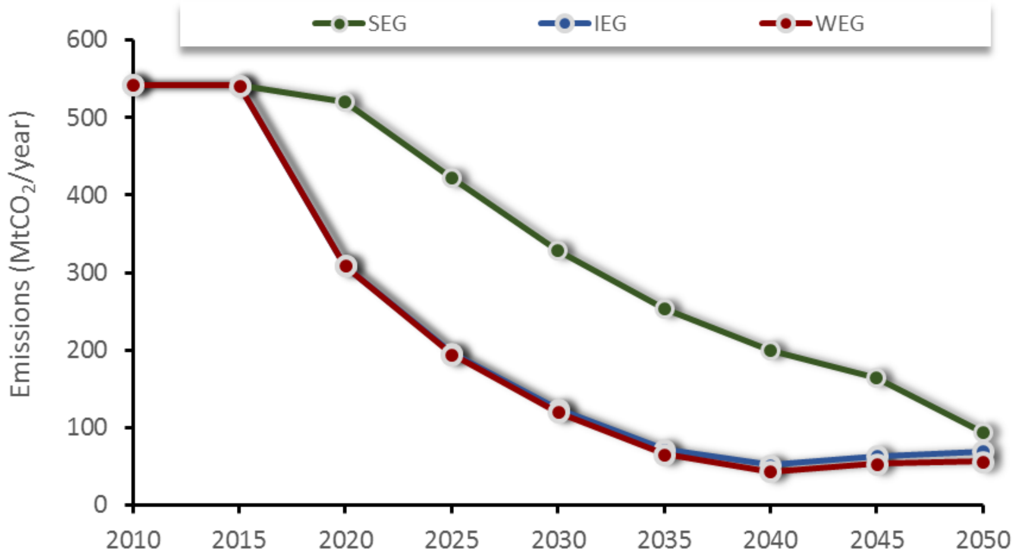

Figure S15 – CO_2 from energy-related emissions, industrial processes and residues

In the *WEG* scenario, the model was not able to find a solution that keeps emissions within the CO_2 budget available for the energy system, which is the lowest of all three scenarios. Emissions drop until 2030 in the *WEG* just as the *IEG* scenario, however the values beyond that are marginally different. This clearly shows that the mitigation options within the energy sector were almost saturated in the *IEG* scenario and, even by completely using all technological possibilities within the model, the *WEG* scenario is inconsistent with the 2°C objective. The cumulative CO_2 emissions from the energy system in the *WEG* scenario correspond to 7.5 Gt CO_2, which overshoots the average value for the CO_2 budget showed in Table S1. This accounts, to some extent, for the uncertainty in the range of values for aggregate CO_2 budget across studies, in which less stringent values (e.g. the results for IMAGE and PRIMAP, see Table S1) would still be consistent with the 2°C global objective.

Figure S16 presents the evolution of primary energy consumption in Brazil for all three scenarios. All scenarios present more or less the same behavior: decreasing fossil-fuel consumption, specially coal and oil, and significantly increasing the role of bioenergy. Also, findings show that as the available CO_2 budget for the energy system decreases, the share of non-biomass renewables increases.

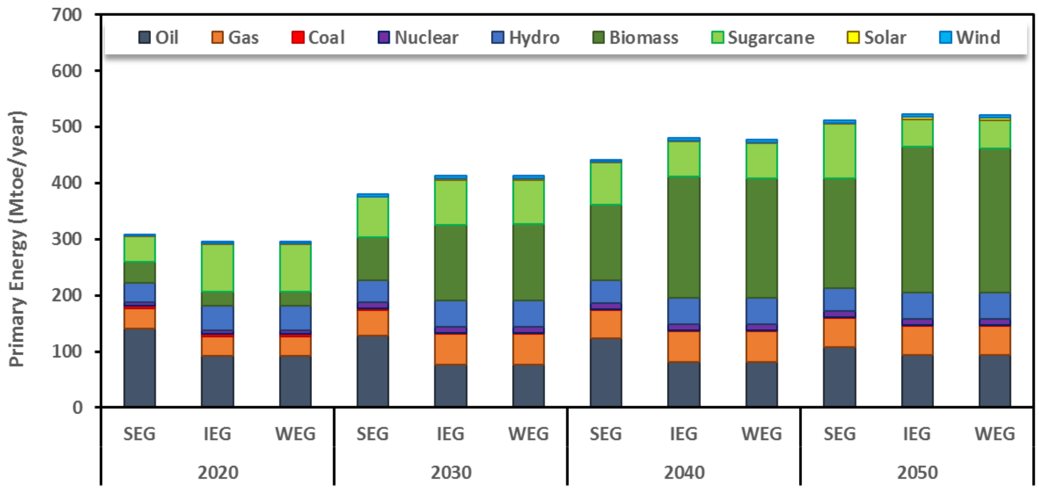

Figure S16 – Primary energy consumption (Mtoe/year) for Brazil

The results for electricity generation (Figure S17) show that electricity demand is larger in the *IEG* and *WEG* scenarios, when compared to the *SEG* scenario. This is associated with the penetration of electric vehicles, as will be explored later in this supplementary material. Another finding of this study is the increased role of renewables, such as wind, solar photovoltaics (PV – in distributed generation - DG) and sugarcane bagasse, which is preferably used for electricity generation instead of second generation ethanol production. Hydro-based generation has a mild increase, mostly resulting from repowering of old power plants. The expansion of nuclear power plants is consistent amongst all three scenarios, reaching almost 4.5 GW in 2050.

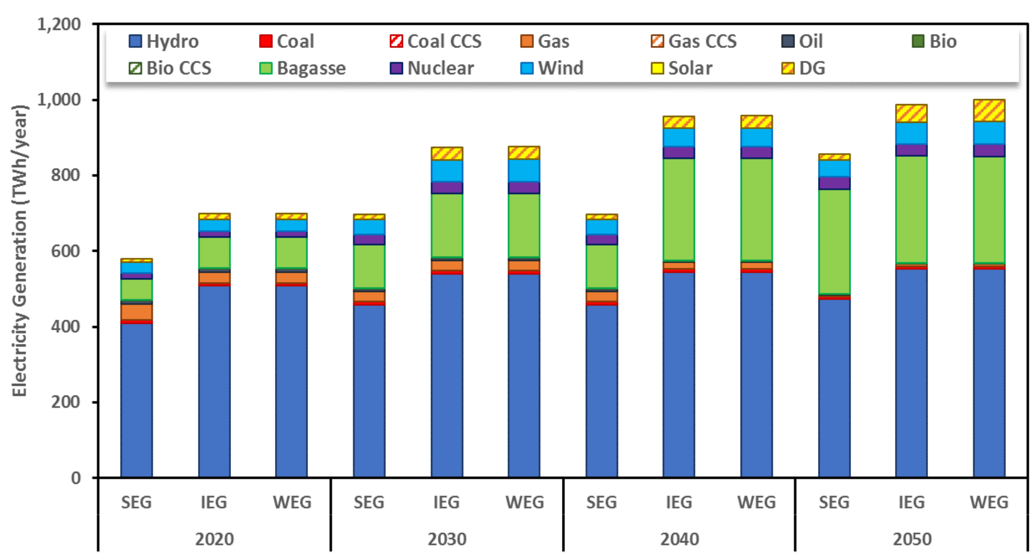

Figure S17 – Electricity generation (TWh/year) in Brazil

Note: CCS – carbon capture and storage; Bio – biomass (except for bagasse from sugar cane); DG – solar PV distributed generation.

As shown in Figure S16, bioenergy becomes a major component of the overall primary energy consumption in all three scenarios. This is due to the production of liquid biofuels, as detailed in Figure S18, which separates biofuels in three categories: ethanol, kerosene and diesel substitutes. Ethanol continues to play a major role in the Brazilian energy system, despite a reduction in the *IEG* and *WEG* scenarios, mostly due to the increased share of electric-based vehicles. In all three scenarios, a small share of the ethanol is produced from second generation, whilst the majority is produced with the association of carbon capture and storage (CCS).

Actually, although available in the technology portfolio of the BLUES model, second-generation ethanol has a timid expansion. Most of the advanced liquid biofuels expansion with CCS is associated with diesel production. There are three main reasons for that: firstly, as of today, ethanol is mostly used by light-duty vehicles (LDVs), which are fully electrified in the most stringent scenarios; secondly, sugarcane bagasse, which is associated with sugarcane production, is picked by the model to produce carbon neutral electricity for the power sector; thirdly, most of the CCS infrastructure (transportation and storage), whose capacity expansion is limited by capital constrains for each model period, is used by the CO_2 captured from BTL diesel production, since there is no easy replacement for this latter fuel used in heavy-duty vehicles (HDVs). Diesel is the most important final energy carrier in Brazil today and in all scenarios.

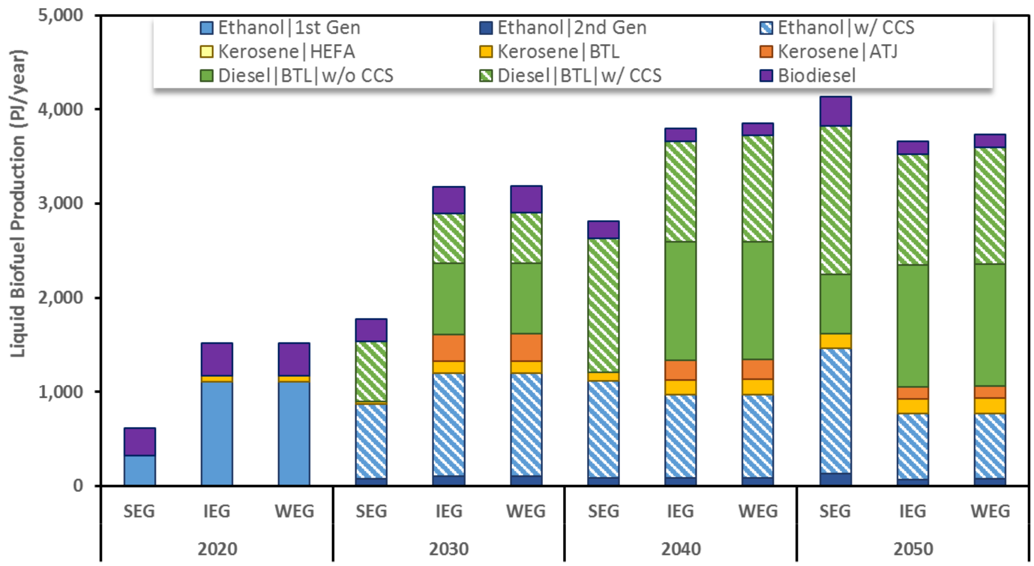

Figure S18 – Liquid biofuel production (PJ/year) in Brazil

Note: Ethanol w/CCS – ethanol from fermentation of sugar with carbon capture and storage; Ethanol/2nd Gen – 2nd generation ethanol from the hydrolysis of sugarcane bagasse; Biodiesel – fatty acid metil ester (FAME) mostly from soy; HEFA – Hydroprocessed Esters and Fatty Acids; Kerosene/BTL – biomass to liquids (Fischer-Tropsch Synthetic Paraffinic Kerosene); Kerosene/ATJ – Alcohol to Jet; Diesel/BTL w/CCS – biomass to liquids (Fischer-Tropsch Synthetic Paraffinic Diesel with with carbon capture and storage); Diesel/BTL w/o CCS – biomass to liquids (Fischer-Tropsch Synthetic Paraffinic Diesel with without carbon capture and storage).

Biokerosene production from Fischer-Tropsch is consistent across all scenarios, however the scenarios with lowest CO_2 budgets also present significant production of Alcohol-to-Jet (ATJ), which uses ethanol produced with CCS as feedstock and, therefore, yield net negative emissions. Thus, it is worth noting that a fraction of the ethanol produced is not seen in the model as final energy, but as a secondary energy source to be converted to jet fuel, through the ATJ route. Nonetheless, the largest share of the biofuel production is related to green diesel from Biomass-to-Liquid (BTL) plants, with or without CCS (depending on the relative cost of carbon transportation and injection). Biodiesel production remains relatively the same across scenarios, with its decreasing role associated with the lower share of fossil diesel in the market.

The results for electricity generation and biofuel production indicate that the Transportation sector has a transformative role in the pursuit to limiting the increase in temperature under 2°C. Thus, biofuels are essential to decarbonize freight transportation and aviation, for which there are fewer alternatives. To reduce emission from diesel production and consumption, the model chooses BTL diesel to allow for neutral CO2 emissions (BTL only, or without CCS) and for negative CO2 emissions (BTL plus CCS). As the CCS infrastructure is limited by capital constrains for each period and for each region, the model has to produce all diesel possible from BTL with and without CCS, to reduce, at a maximum, CO_2 emissions from its consumption.

Figure S19 presents the evolution of energy consumption in the Transportation sector. The major finding shown in this figure is the increasing role of electricity across the increased deforestation scenarios, in which each scenario with lower CO_2 budget presents a higher penetration of electric-based vehicles. As electric-driven vehicles are much more efficient than internal combustion engines vehicles, final energy decreases for passenger transportation. Moreover, in the *IEG* scenario, this penetration would start as early as 2020, if Brazil intends to compensate for the additional emissions from deforestation. This is a heroic result, given Brazil's current light-duty vehicles fleet based on flex-fuel cars, its car manufacturing industry having no production lines dedicate to electric-cars[86], the lack of electric-power infrastructure[87] and the absence of policies to support electric-driven vehicles in Brazil [88-90].

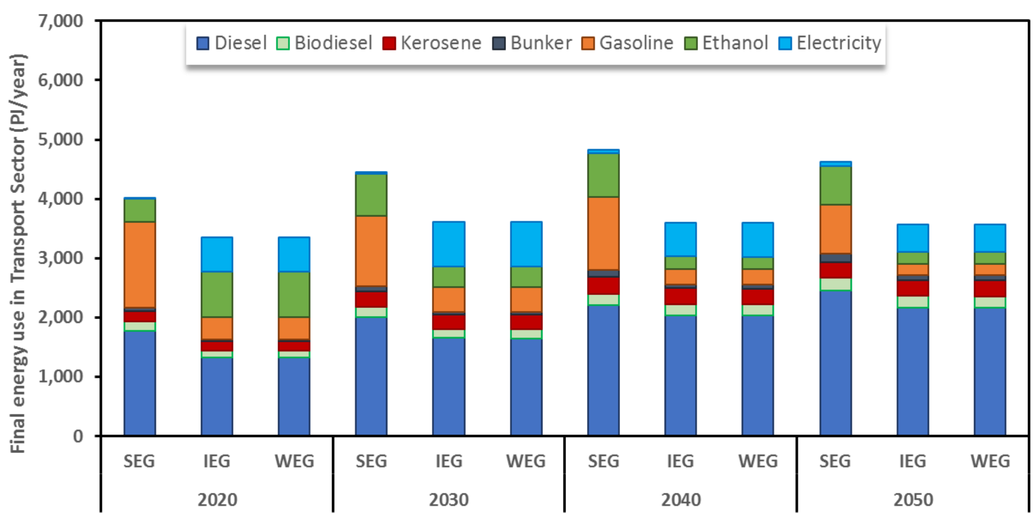

Figure S19 – Transport sector final energy consumption (PJ/year) in Brazil

Notes: Diesel and Kerosene – final energy that can derive from fossil fuel and/or biomass primary energy sources. See Figure S15 for the biomass origins of these final energy sources in the WEG and IEG scenarios.

Figure S19 also presents a marginally lower consumption of diesel across scenarios. However, as mentioned previously, the share of diesel from biomass (BTL with or without CCS) increases as the consumption decreases. Therefore, the higher penetration of electric-based vehicles and higher share of advanced biofuels significantly reduce the emissions from the Transportation sector, as shown in Figure

S20 A. This figure shows how the CO_2 emissions from the *IEG* are almost 70% lower than the *SEG* scenario, whilst the *WEG* is only 2% lower than the first.

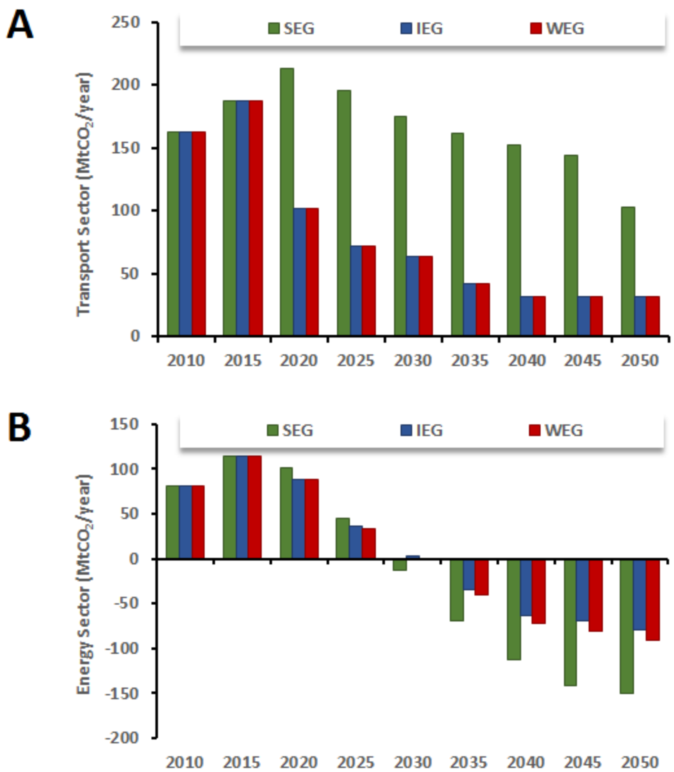

Figure S20 – Carbon emissions from Transport sector (A) and Energy sector (B), in Mt CO_2/year

Figure S20 B presents the CO_2 emissions from the energy sector, which includes the power sector, fuel manufacturing sectors and the CCS infrastructure. Negative emissions from advanced biofuel production with carbon capture are accounted in this sector. Results show that the lower production of ethanol with CCS reduces the role of net negative emission technologies, despite the increase in advanced biofuels, especially diesel, in the *IEG* and *WEG* scenarios. In fact, the production of diesel from BTL with CCS in all three scenarios is relatively the same, with the *IEG* and *WEG* increasing advanced diesel production with BTL without CCS.

Therefore, the overall deployment of BECCS in the alternative scenarios is lower than the *SEG* scenario. These results are confirmed in Figure S21, which presents the results of the CCS deployment in all scenarios. As can be seen, the use of BECCS is lower in the *IEG* and *WEG* scenario, therefore the negative contribution of the energy system emission is also lower. Thus, the reduction in emissions from the transportation sector in the *IEG* and *WEG* scenarios (Figure S20 A) more than compensated the increase in the emissions of the energy sector due to the lower deployment of BECCS (Figure S20 B).

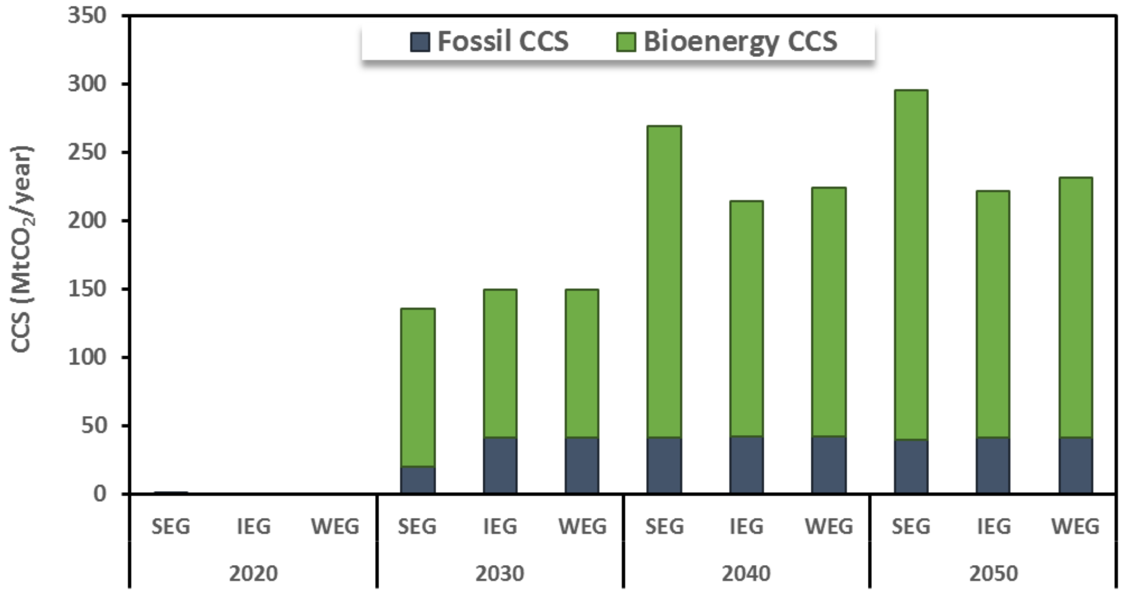

Figure S21 – CCS deployment across scenarios by type in Mt CO_2/year

Once more results show that the results from the *WEG* are marginally different than the *IEG* scenario. This indicates that the mitigation strategies available in the modelling framework are already reaching their maximum reduction in CO_2 emissions from the energy system and, therefore, it is infeasible to keep emissions under the CO_2 budget in the *WEG* scenario.

The results for the deforestation reversal scenarios also show that reducing CO_2 emissions in other sectors would rely on the deployment of disruptive and not yet fully mature technological options, such as advanced biofuels, CCS, electric vehicles, etc. This illustrates the level of effort needed to compensate for higher emissions from LULUCF, which can, in turn, lead to high investment costs and the need for research and development (R&D). Table S4 shows the estimated investment costs (not considering R&D) in all scenarios projected in this study.

Results show that the investment costs for the energy system almost double under the *IEG* and *WEG* scenarios, when compared to investment costs of the *SEG* scenario. The increase in investments is highly concentrated on the energy sector, considering both power and fuel production. Additionally, the total investment in the *WEG* scenario is marginally higher (roughly 2%) than in the *IEG* scenario, which, once again, indicates a saturation of the mitigation opportunities.

Lastly, as mentioned before, the *WEG* scenario was not able to fulfill the necessary CO_2 budget requirement for Brazil. Hence, the optimization in the BLUES model would be infeasible, if soft constraints were not added to enable the simulation. Therefore, the *WEG* scenario is associated with a non-commitment cost for failing to comply with Brazil's CO_2 budget proposed in this study, which, if accounted, would highly exceed the observed total costs.

One possible narrative is that, under this scenario, the rest of the world would need to reduce its emissions to compensate for Brazil not accomplishing its part. Therefore, Brazil could still fulfill its commitment by paying third parties to reduce their emissions in its place. We estimated this additional cost as equivalent to carbon price in trajectories consistent with a “below 2°C” world.

Therefore, using the mean value (370 US$/t$CO_2$) and the range of carbon prices available in Figure S4 (162 to 505 US$/t$CO_2$), the total cost in the *WEG* scenario could vary from 2.1 to 3.3 times the total cost in the *SEG* scenario, with a mean value of 2.8 times (Table S4). This situation is further explored in the section “Limitation of the Study and Sensitivity Analyses”.

Table S4 – Total costs across scenarios

Sector	SEG (10^9 US$$_{2010}$)		IEG (10^9 US$$_{2010}$)		WEG (10^9 US$$_{2010}$)	
	Investment	O&M	Investment	O&M	Investment	O&M
Fuels[1]	622	381	1,132	418	1,142	417
Power	367	86	641	109	675	109
Industrial	48	52	49	65	49	65
Others	164	136	167	137	167	138
Penalty	-	-	-	-	-	2,440 (1,069-3,333)[2]
Total	1,201	654	1,989	729	2,033	3,169 (1,798-4,062)[2]

Note: 1 – Fuels Sector include primary energy production, oil refineries, biofuel production and energy-related CCS infrastructure; 2 – Values relative to median, 25th and 75th percentile of the carbon price (respectively). See Figure S1.

It is worth noting that the implementation costs of avoiding deforestation are not considered in the total cost. In fact, there is evidence that the economic cost of reducing deforestation is very low and for this reason does not need to be accounted in the model. Between 2000 and 2014, the budget from all federal agencies in the country related to deforestation reduction policies increased from nearly US$ 500 million, in 2000, to above 1 billion in 2011[91]. These investments help to explain why deforestation dropped by more than 70% in the same period. However, although environmental spending doubled, it still represented less than 0.01 percent of the country’s public spending. Furthermore, most deforestation reduction policies, such as the creation of protected areas in undesignated public lands and the creation of environmental requirements for the provision of public bank loans to farmers do not involve direct costs. For this reason, this study argues that the main cost for reducing deforestation in Brazil is mostly political, as it involves challenging the powerful lobby of the rural caucus in the Brazilian congress.

S3. Supplementary Discussion

Limitation of the Study and Sensitivity Analyses

Roughly, a so-complex study has several limitations. The major ones are the budget associated with the 2°C target, the representation of technological disruptive innovations, the availability of energy resources and technology costs. We also assess the limitations related to the costs of reaching the *WEG* scenario and the uncertainty related to pasture intensification.

In terms of our own modelling effort, it is worth saying that we recognize the need to implement some probabilistic and risk analyses in our model[92]. However, this is not trivial, given the large level of detail in the technological representation and the high number of key variables within the BLUES model. IAMs, national or global, seldom implemented probabilistic runs, given the large number of technological nodes inside them. As detailed before, BLUES is a very technological detailed model.

Finally, we have conducted two main sensitivity analyses to address two major sources of uncertainties of this study: one related to negative CO_2 emissions and the other related to the Brazilian CO_2 budget itself.

Carbon Budget

Firstly, the most recent scientific literature discusses the uncertainty of the various methods to estimate carbon budgets associated with keeping global warming to below a given temperature limit. The literature on carbon budgets shows a very strong relationship between cumulative CO_2 emissions and temperature increase and radiative forcing[23]. The uncertainty in the almost linear relationship between cumulative CO_2 emissions and temperature increase manifests itself in basically two ways [93]: (1) the uncertainty in the slope of this relationship caused by the uncertainty in the climate system response, and (2) the uncertainty in this relationship due to differences in the timing of emission reductions and reduction in non-CO_2 gases over time.

There is relatively large consensus in the international literature on the global CO_2 budget associated with a 2^{o}C temperature increase under a range of probability values[94]. However, in the case of emission budgets and pathways consistent with limiting warming to 1.5^{o}C, recent studies indicate the possibility of much higher cumulative post-2015 CO_2 emissions than had, so far, been considered[94].

In our study, we decided to use the CO_2 global consistent with a >67% probability of limiting average surface warming to below 2^{o}C by the end of this century. This is higher than the most generous cumulative post-2015 CO_2 emissions found in the literature to limit post-2015 warming to less than 0.6^{o}C by 2100, to limit average surface warming to 1.5^{o}C above pre-industrial levels by that same year [94], and so it is a conservative approach from our side which supports the conclusions of this study. In sum, clearly temperature increases, and related CO_2 budgets are sources of uncertainty, but we decided to control these uncertainties by relying on the recently compiled IPCC scenario database[93], which is a well-established, and conservative, CO_2 budget.

As previously mentioned, the studies that have translated the global CO_2 budget for a 2^{o}C temperature increase into a value for Brazil show a spread of values, which can lead to some uncertainty on the actual effort of the country under the global climate commitment. The results found for the *WEG* scenario shed some light into this matter, since its overshoot actually keeps total Brazilian emissions within the less stringent values for the national carbon budget (see Table S1). On the other hand, a more stringent budget would mean that deforestation reversal scenarios would become less likely feasible. We have performed a sensitivity analysis on Brazil´s CO_2 budget, which is detailed in the end of this section in order to put a figure on this discussion.

Technological Disruptive Innovations

It is a complex effort to predict all possible technologies (on the supply and on the demand side) that will be technically available until 2050. However, BLUES has a much more detailed technological structure than most national IAMs do, including various not yet mature technological options.

1. For instance, in the case of petroleum refineries, usually the other models follow a very simplified structure not able to evaluate the operational degree of flexibility of these energy and non-energy conversion facilities (Figure S22 A). This is not the case of BLUES, which not only details the production basket of the refineries but also their utilities, being able to incorporate carbon capture in FCC and hydrogen generation units (Figure S22 B).

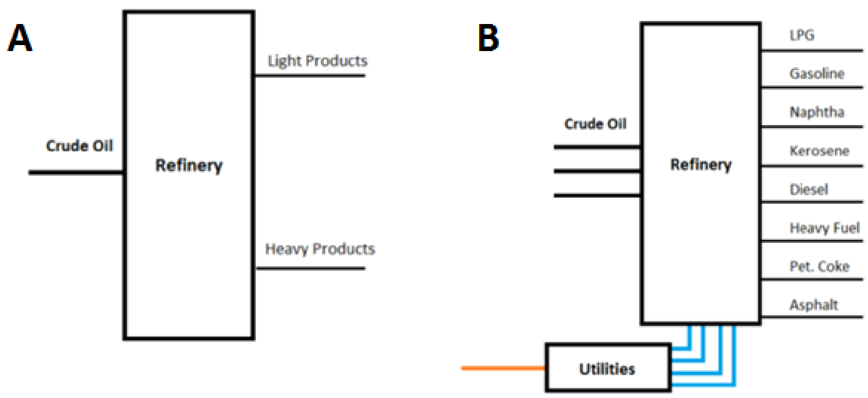

Figure S22 – Refinery schemes in a typical IAM (A) and in BLUES (B)

2. In the case of electricity generation, BLUES includes several electricity generation options, with a suitable level of detail (e.g. four types of concentrated solar power plants, including hybridization with biomass; co-burning of coal and biomass in thermal power plants; CCS in coal, biomass, and natural gas fired-generation, flexible and non-flexible combined cycle plants; onshore and offshore wind plants, only to cite a few). It also details the transport of electricity, crude oil and oil products, natural gas and CO_2 between Brazilian regions.
3. In the case of biofuels, BLUES has not only first-generation liquid biofuel options (ethanol from sugar cane and FAME and FAEE), but also advanced options, including FT-jet fuel, FT-diesel, FT-Naphtha, Alcohol to Jet fuel, HEFA, and biobunker. For first-generation ethanol and all FT-fuels, carbon capture is available.
4. On the demand side, there are more than 700 options for fuel saving in industry and buildings. The industrial sector is split into 11 subsectors, and includes carbon capture options in cement, steelmaking and ammonia plants. In the case of the transportation sector, passenger private transportation modes include light-duty-vehicles (LDVs), motorcycles, while passenger public transportation includes buses, micro-buses, subways (metro), rail, airplane and boats. LDVs can be powered by gasoline, ethanol, flex (ethanol and gasoline), hybrid, plug-in hybrid and battery electric vehicles. Motorcycles can be either fueled by gasoline, flex or electric. Buses can be powered by diesel, ethanol, biodiesel, and electricity. Therefore, the model is able to opt to electric-modes of transportation.

Clearly, there are always new technological options to include in IAMs. The basic procedure is to design the energy, mass and cost balances of these options and to insert them as a new technological node in the model. However, we are quite confident that for the horizon of 2050 we have designed and incorporated a vast range of not yet mature technologies, considering the Brazilian and even the world contexts.

Energy Resources

Fossil and renewable energy resources are inputs for the optimization model. In the case of crude oil and gas, we have used a detailed non-public database of discovered Brazilian fields (almost 60 billion bbl of ultimately recoverable resources) to build a bottom up analysis of discovered resources and develop a marginal supply curve (Figure S23).

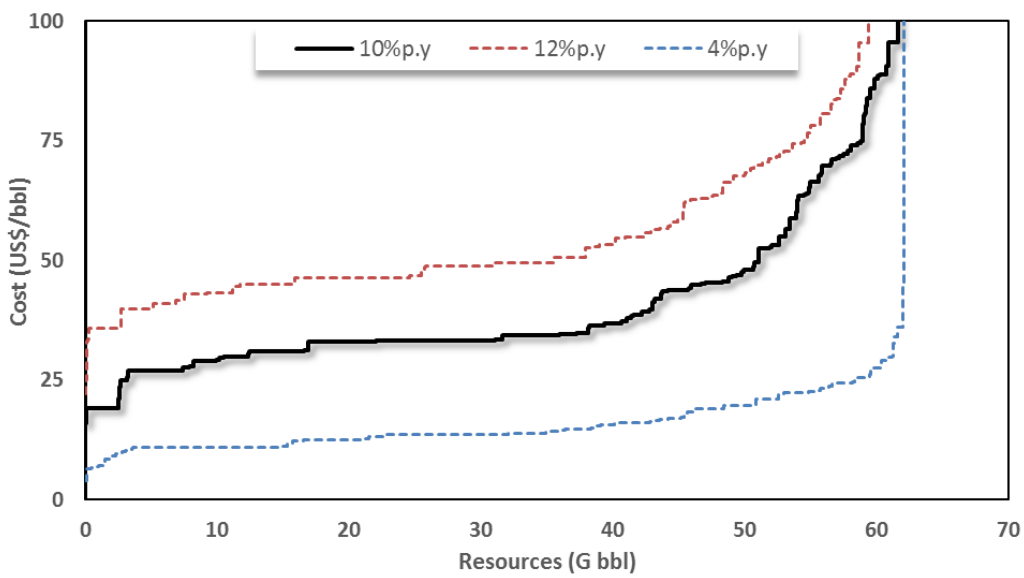

Figure S23 – Supply curve for crude oil in BLUES

To the discovered petroleum resources, we have added the ultimately recoverable resources (URR) of yet-to-find and enhanced oil recovery (EOR) contingent resources of 7 Gbbl. These last resources represent the major source of uncertainty in the fossil fuel resources inserted in BLUES. Nevertheless, in the results of the three scenarios, cumulative petroleum production reached 51 Gbbl, which is roughly 80% of the URR of the discovered resources. This means that the uncertainty related to EOR and yet-to find resources have not affected our findings.

In the case of the hydropower, we have allowed the model to repower existing plants but limited the remaining potential for new hydropower plants in the Amazon biome to 20 GW[95]. In the case of wind resources, the regional potential inserted in BLUES is detailed according to the average capacity factor (Figure S24). As for solar resources, Figure S25 presents the supply curve for distributed generation with PV technology in terms of the levelized cost.

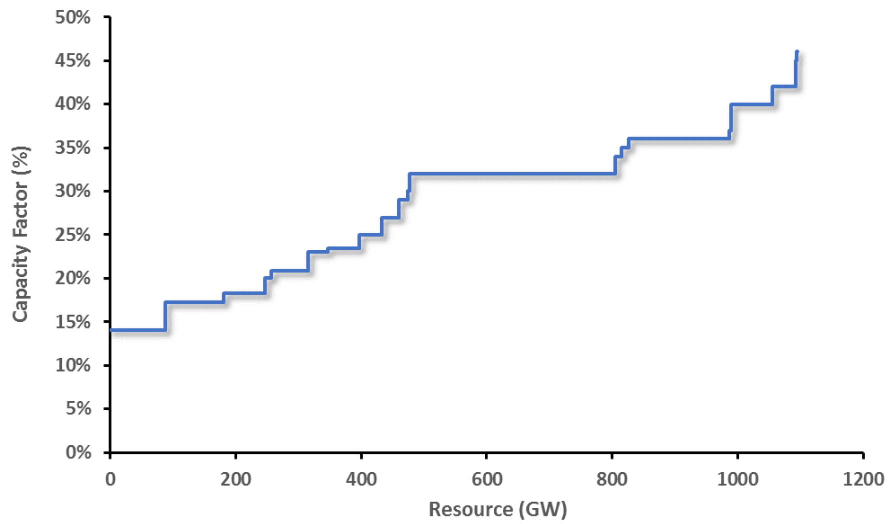

Figure S24 – Supply curve for onshore wind in BLUES

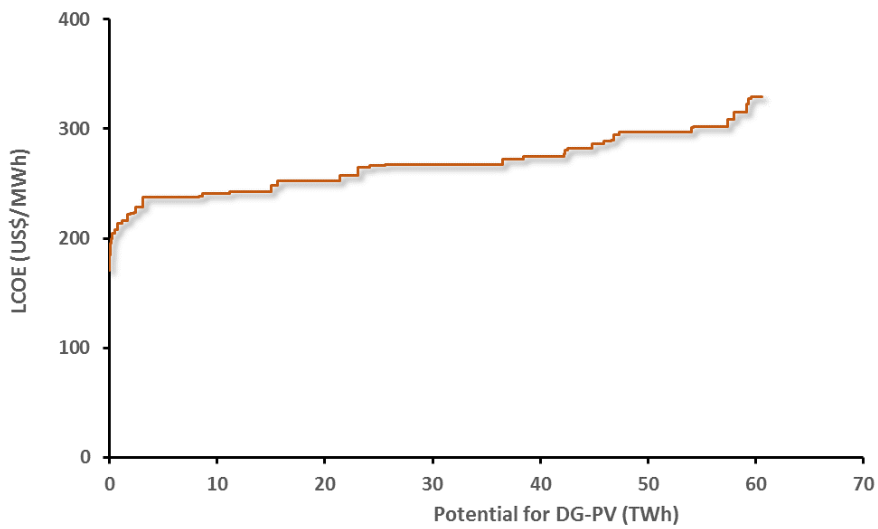

Figure S25 – Supply curve for distributed generation (PV) in BLUES

Once again, the cumulative use of wind and solar in the three scenarios was just a fraction of their thermodynamic potential. In other words, it is not the resource potential that is constraining the use of fossil and renewable energy sources in our runs, but the technical feasibility of their use. This is particularly worthwhile in the case of centralized solar PV and wind power plants, whose production is capped to 25% of the total electricity generation in Brazil. This cap derives from the results of a dispatch model developed for the Brazilian electric power system[57]. A large deployment of large scale batteries or compressed air systems would increase this cap perhaps in 5%[96]. However, this technological breakthrough is still far from reality in Brazil and likely will not solve the issue of infeasibility of the last scenario run by us.

As for modelling CCS in BLUES, there are restrictions in place that limit the potential growth of deployment of the technology. Primarily, the energy resources themselves (either coal, gas, oil or biomass) are restricted due to their production chain, availability and production costs. Secondly, the BLUES model has also restrictions for the growth of the CCS infrastructure, particularly pipelines. The model allows, nationally, for the construction of roughly 20 $MtCO_2$/year of new CO_2 pipelines, from 2020 to 2050. Thus, this would allow for the carbon capture of, roughly, 600 $MtCO_2$/year in 2050. This value is split within all five regions of the model according to each region's potential for geological storage, leading to a higher share in the northeast and southeast regions.

Cost of Technological Options

Cost is always an important source of uncertainty when it comes to not yet mature options and the need to account for pioneer plants[97]. We have tried to control this important issue by comparing our data to the data of other models in the major modeling effort of the CD-links project. Nevertheless, we do recognize that in Brazil location cost factors may be important, given the country's labor and capital productivity[92]. Moreover, we also acknowledge that energy megaprojects in Brazil have been facing overrun costs and construction delays[98].

Actually, a recent study[92] tried to incorporate this issue, by running BLUES using cost frequency distribution to energy megaprojects derived from a statistical analysis[98], which has shown that energy megaprojects costs follow a non-symmetrical frequency distribution[1]. The main result was that large coal fired thermal power plants, nuclear and hydropower plants were replaced by wind and solar PV, when cost overruns are accounted for. Moreover, petroleum refineries are not expanded, and Brazil increases its distillate fuel dependency[92].

The results show that cost uncertainties can affect the choices made by BLUES[98]. However, they would not affect the basic results of the *IEG* scenario, simply because this scenario is already using wind and solar PV options to the cap of the electricity generation. This means that assuming an increase in deforestation in Brazil, the effort to stay in the Brazilian CO_2 budget already boosts the use of PV and wind to their cap. In other words, accounting for the overrun costs would not increase their use. The same would be the case for technological development and cost reductions in solar PV and wind. Moreover, the cost uncertainty does not affect the infeasibility of the *WEG* scenario. The least-cost solution of the optimization model, given the constraints, allows the model to find the technological portfolio no matter the overrun costs. In the *WEG* scenario, the model was not able to find a technological solution for the remaining CO_2 budget even with several options from the demand and the supply side. This is not related to cost, but to technical potential.

Brazilian Cost under the WEG Scenario

In our runs we have found that, in the *WEG* scenario, Brazil would not be able to meet the target established for its share of the global 2°C budget. Thus, we have defined this scenario as infeasible. One possibility would be for the rest of the world to reduce its emissions to compensate for Brazil not doing

[1] For instance, the parametric distribution that best fit the cost overruns data of hydropower projects in Brazil was the gamma distribution, $X \sim (\kappa = 0.876, \theta = 125)$.[98] This means that "policy makers should increase their budgets by around 75% above the initial budget to get 50% certainty that their final costs will be within budget. If decision-makers are more risk tolerant, they should apply a 30% increase in the initial budget; however, they will have a 75% chance of obtaining a final cost that exceeds this value. The more conservative, risk averse, should raise their costs initially estimated at 180% to be 80% sure that they did not exceed their budget".

its part. Literature review indicate a median price of 370 US$/t$CO_2$, in 2050, for a "below 2°C" world (Figure S4). Therefore, should Brazil fulfill its commitment by paying third parties to reduce their emissions in its place at the market carbon cost, this would imply in an additional cost of about 2,440 billion US$ to the *WEG* scenario.

However, as shown in Figure S4, there are considerable uncertainties related to the CO_2 price associated with a "below 2°C" scenario in 2050. For instance, the values of the CO_2 price in the 25th and 75th percentiles are 162 US$/t$CO_2$ and 505 US$/t$CO_2$, respectively. These values would result in additional cost ranging from 1,069 to 3,333 billion US$. Furthermore, Figure S4 indicates a carbon price range in 2050 (beyond the 25th and 75th percentiles) of 60 US$/t$CO_2$ to 1455 US$/t$CO_2$. This would lead to a penalty cost, in the *WEG* scenario, hovering between 396 and 9,530 billion US$.

Additionally, the narrative used in the above estimations were based not only on the availability of third parties that would be willing to compensate for the additional CO_2 emissions from Brazil, but also that the negotiations would be based on a carbon price, which would be derived from results of integrated assessment models. The additional layer of uncertainties in alternative narratives that are not based on such assumptions are overwhelmingly higher and, therefore, not subject to analysis in this study.

Pasture Intensification

There is significant uncertainty involving natural carbon sinks, related to afforestation and other land uses. It is unlikely that high-deforestation scenarios (*IEG* and *WEG*) would include any afforestation. However, some emissions reduction measures that enhance existing sinks may occur in the agricultural sector. One case is recuperation of degraded lands leading to higher biomass and soil organic carbon content. In Brazil, recuperation of degraded pastures is an example of such an activity and is the cornerstone of the low-carbon agriculture plan (Plano ABC)[100]. Between 83.0 and 104.0 Mt CO_{2e} of the Plan's total mitigation targets of between 133.9 and 162.9 Mt CO_{2e} by 2020 are projected to come from degraded pasture recuperation.

About half of Brazil's 220 Mha of pastures are considered degraded (defined as below their potential carrying capacity) and about 52 Mha are in an advanced state of degradation[101,102]. The total mitigation potential of recuperation of these worst cases is estimated between 1 and 1.5 tC per hectare per year for a period of 10 years[101], which would lead to emission reductions of between 1.9 and 2.9 Gt CO_2 by 2030. This represents about 10% of the average carbon budget used in this study, which is a value well within the uncertainty range of such estimates. Therefore, we opted to not consider this in the emissions estimates. Anyway, this only represents about one years' worth of total Brazilian emissions at current levels. Moreover, the inclusion of this buffer does not change the infeasibility of the *WEG* scenario, that is, subtracting this value from the projected emissions does not allow the model to find a solution reaching the target budget.

Sensitivity Analyses

The original scenarios presented a large amount of BECCS, but the overall amount of CCS deployment was relatively the same across the scenarios. Even though results show that the model did not approach the national maximum capacity in 2050 (see Figure S21 and the "*Energy Resources*" section), the results could still be limited by a regional constraint on the growth rate of CCS, restricting the overall deployment of CCS. Thus, perhaps more CO_2 transportation capacity could allow more BECCS and make scenario *WEG* feasible. Therefore, a new set of runs for the BLUES model was conducted, with less stringent constrains on the CO_2 infrastructure (**Sensitivity Analysis 1**). In this case, the CCS restriction was doubled from 2020 to 2050, from roughly 20 $MtCO_2$/year to 40 $MtCO_2$/year. This would lead to a total potential capacity for CO_2 pipelines in 2050 of around 1,200 Mt CO_2 (instead of about 600 $MtCO_2$ that was set in the original runs of BLUES).

In addition, as mentioned before, there are many uncertainties associated with the assumed Brazilian carbon budget for a "below 2°C" world. This is a major and up-front source of uncertainty, which affects the main findings of this study. In the original runs (*SEG*, *IEG* and *WEG*), an average value of the literature for the Brazilian carbon budget was used. In order to assess the role of the uncertainty in the national budget, two new budget cases are proposed: a low budget, or LB, case, set according to the 25% percentile (equal to 16.5 $GtCO_2$ up to 2050), and a high budget, or HB, case, set according to the 75% percentile (equal to 35.5 $GtCO_2$ up to 2050). Therefore, 6 additional runs were performed, considering the three scenarios of environmental governance (SEG, IEG and WEG), and the two new Brazilian carbon budgets: LB and HB (**Sensitivity Analysis 2**).

a) Results of Sensitivity Analysis 1 (High CCS infrastructure capacity addition): Scenarios SEG-HiCCS, IEG—HiCCS, WEG—HiCCS

In the case of the Sensitivity Analysis 1, even though the restriction that limited the capacity addition of CCS was increased (in fact, doubled), the results showed only an almost insignificant increase in the CO_2 transportation and storage activity in all scenarios. For instance, in the original IEG scenario presented the capture of around 220 $MtCO_2$/year in 2050, while in the IEG-HiCCS scenario this value went up by around 25 $MtCO_2$/year. In all three scenarios of the Sensitivity Analysis 1, the increase of CCS was fully attributed to BTL plants with carbon capture.

It is also worth noting that any increase in CCS only appeared in the Brazilian regions that were more strongly constrained in the original model, due to their relative lower production capacity and geological storage potential (namely, the North and Center-West regions). In other words, the relaxation of the former constraint on the CO_2 transportation capacity addition did not affect the CCS level practiced in the Southeast and Northeast regions, which concentrate most of the CCS installed capacity and of the potential for geological storage.

In fact, the most reasonable explanation for the relative small effect of the sensitivity analysis on the CCS penetration is also related to another constrain in the model: on the capacity addition of advanced biofuels (with or without carbon capture). According to the assumptions made in BLUES, each Brazilian region can add a plant of around 150 thousand barrels per day (kbpd) in a 5-year period. In other words, nationally the model allows for the addition of 750 kbpd every five years (due to the five Brazilian regions). This constraint is widely optimistic, especially considering recent studies that highlight the struggles related to the construction of large-scale liquid fuel plants in Brazil[92,96]. Thus, a sensitivity analysis for this variable was not conducted.

Nonetheless, the small effect in deployment of CCS led to somewhat considerable effects in costs for the WEG-HiCCS scenario. It is worth reminding that the *WEG* scenario was not able to meet the determined national carbon budget and, therefore, was accounted with a penalty cost for the exceeding CO_2 emissions. However, since the *WEG-HiCCS* scenario allowed Brazil to reduce its emissions even further thanks to the additional BECCS, the extra cost of not complying with an international agreement and/or the payment of exceeding emissions by Brazil were smaller in the *WEG-HiCCS* scenario than in the WEG scenario.

b) Results of Sensitivity Analysis 2 (High and Low Budget): Scenarios SEG_LB, IEG_LB, WEG_LB; and SEG_HB, IEG_HB, WEG_HB

This section addresses first the results for the Low Budget (16.5 $GtCO_2$) scenarios *(SEG_LB*, *IEG_LB*, *WEG_LB*). An evaluation of the original results could anticipate that some scenarios would be highly stressed by a reduction in the carbon emission allowance. Although feasible, the scenario *SEG-LB* presented a cost much higher than the original SEG scenario, an increase similar to the original *IEG* and *SEG*. In fact, the available budget for the energy system in the *SEG-LB* (dropped from 14.4, in the original *SEG*, to 6.9 $GtCO_2$) and the original IEG (7.7 $GtCO_2$) are very similar, which led to relatively the same results. On the other hand, unlike the original IEG, the IEG-LB was not able to stay below the CO_2 emission budget by 7.4 $GtCO_2$, a value higher than the exceeding emission of the original *WEG*. Finally, the *WEG-LB* was not able to meet the budget, as expected since the budget available for the energy system is even lower than the original *WEG*.

As for the scenarios with the High Budget (35.5 $GtCO_2$), all three deforestation scenarios are theoretically compatible with the national budget for a "below 2°C" world (*SEG_HB, IEG_HB, WEG_HB*). Just to illustrate, the available budget for the energy system in the more stringent scenario, *WEG-HB*, is of about 12.5 $GtCO_2$, whist in the original less stringent scenario, *SEG*, was of about 14.4 $GtCO_2$. That is, under a higher budget consideration, the scenario with the highest deforestation (*WEG_HB*) is only marginally more restricted in CO_2 emissions than the original scenario with the lowest deforestation rates (*SEG*, under the average carbon budget). Thus, all three scenarios are feasible under the Higher Budget (*HB*) sensitivity analysis.

Finally, this sensitivity analysis allowed for a critical assessment of a variable that is fundamental to this study, namely, the Brazilian share of CO_2 emissions budget for a "below 2°C" world. However, it must be noted that this study does not address the challenges in creating an ethical and easily accepted metric for sharing the global CO_2 emissions across nations.

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Supplementary Annex – Capital Cost for Energy Technologies (CD-Links template)

Table S5 – Capital Cost for Energy Technologies (CD-Links template)

Technology	Unit	2010	2020	2030	2040	2050	Description of Variable
Electricity|Biomass|w/o CCS|1	US$/kW[1]	868	868	868	868	868	New bagasse cogeneration plant, low efficiency, without CCS.
Electricity|Biomass|w/o CCS|2	US$/kW[1]	987	987	987	987	987	New bagasse cogeneration plant, medium efficiency, without CCS.
Electricity|Biomass|w/o CCS|3	US$/kW[1]	1,505	1,505	1,505	1,505	1,505	New bagasse cogeneration plant, high efficiency, without CCS.
Electricity|Biomass|w/o CCS|4	US$/kW[1]	4,665	4,665	4,665	4,665	4,665	New biomass power plant without CCS.
Electricity|Biomass|w/ CCS	US$/kW[1]	5,965	5,965	5,965	5,965	5,965	New biomass power plant with CCS. Post-combustion capture.
Electricity|Coal|w/ CCS|1	US$/kW[1]	4,275	4,275	4,275	3,563	3,563	New high grade coal power plant with CCS. Subcritical PC with post-combustion capture.
Electricity|Coal|w/ CCS|2	US$/kW[1]	5,250	4,725	4,725	3,938	3,938	New low grade coal power plant with CCS. Subcritical PC with post-combustion capture.
Electricity|Coal|w/ CCS|3	US$/kW[1]	3,500	3,500	3,500	3,500	3,500	New high grade coal power plant with CCS. IGCC with pre-combustion capture.
Electricity|Coal|w/o CCS|1	US$/kW[1]	2,500	2,500	2,250	1,875	1,875	New high grade coal power plant without CCS. Subcritical PC.
Electricity|Coal|w/o CCS|2	US$/kW[1]	2,500	2,500	2,250	1,875	1,875	New high grade coal power plant without CCS. Subcritical PC with 30%w co-firing.
Electricity|Coal|w/o CCS|3	US$/kW[1]	2,750	2,750	2,475	2,063	2,063	New high grade coal power plant without CCS. Supercritical PC.
Electricity|Coal|w/o CCS|4	US$/kW[1]	3,000	3,000	2,700	2,250	2,250	New low grade coal power plant without CCS. Subcritical PC.
Electricity|Coal|w/o CCS|5	US$/kW[1]	3,000	2,700	2,700	2,250	2,250	New low grade coal power plant without CCS. Subcritical PC with 30%w co-firing.
Electricity|Coal|w/o CCS|6	US$/kW[1]	3,250	3,250	2,925	2,438	2,438	New low grade coal power plant without CCS. Supercritical PC.
Electricity|Coal|w/o CCS|7	US$/kW[1]	2,600	2,600	2,600	2,600	2,600	New high grade coal power plant with CCS. IGCC.
Electricity|Gas|w/ CCS	US$/kW[1]	3,091	3,091	2,790	2,520	2,400	New gas power plant with CCS.
Electricity|Gas|w/o CCS|1	US$/kW[1]	800	800	720	600	600	New gas power plant w/o CCS. Open cycle.
Electricity|Gas|w/o CCS|2	US$/kW[1]	1,190	1,190	1,000	1,000	1,000	New gas power plant w/o CCS. Combined cycle.
Electricity|Gas|w/o CCS|3	US$/kW[1]	1,500	1,500	1,300	1,200	1,200	New gas power plant w/o CCS. Flexible combined-cycle.
Electricity|Hydro|1	US$/kW[1]	2,936	2,936	2,936	2,936	2,936	New small scale hydropower plant.
Electricity|Hydro|2	US$/kW[1]	2,513	2,513	2,513	2,513	2,513	New medium scale hydropower plant.
Electricity|Hydro|3	US$/kW[1]	2,091	2,091	2,091	2,091	2,091	New large scale hydropower plant.
Electricity|Hydro|4	US$/kW[1]	2,650	2,650	2,650	2,650	2,650	New reversible hydropower plant.
Electricity|Hydro|5	US$/kW[1]	5,761	5,761	5,761	5,761	5,761	New hydrokinetic hydropower plant.
Electricity|Nuclear	US$/kW[1]	4,000	4,000	4,000	4,000	4,000	New nuclear power plant. PWR.
Electricity|Solar|CSP|1	US$/kW[1]	6,312	5,298	4,434	4,080	3,912	New concentrated solar power plant. Parabolic Troughs with 7h storage.

Electricity|Solar|CSP|2	US$/kW[1]	7,254	6,055	5,036	4,620	4,422	New concentrated solar power plant. Parabolic Troughs with 12h storage.
Electricity|Solar|CSP|3	US$/kW[1]	11,518	9,614	7,996	7,335	7,021	New concentrated solar power plant. Solar Tower with 12h storage.
Electricity|Solar|CSP|4	US$/kW[1]	5,856	4,919	4,122	3,796	3,641	New concentrated solar power plant. Hybridization with biomass.
Electricity|Solar|PV	US$/kW[1]	4,250	4,250	2,750	1,800	1,400	New solar PV units.
Electricity|Wind|Offshore|1	US$/kW[1]	5,000	4,800	4,000	3,500	3,000	New offshore wind power plants. At 20km from the coast.
Electricity|Wind|Offshore|2	US$/kW[1]	6,500	6,240	5,200	4,550	3,900	New offshore wind power plants. At 50km from the coast.
Electricity|Wind|Offshore|3	US$/kW[1]	9,000	8,640	7,200	6,300	5,400	New offshore wind power plants. At 100km from the coast.
Electricity|Wind|Onshore	US$/kW[1]	2,517	2,290	2,114	2,001	1,938	New onshore wind power plants.
Hydrogen|Gas|w/ CCS	US$/kW[1]	622	622	622	622	622	New gas to hydrogen plant with CCS. Methane steam reforming.
Hydrogen|Gas|w/o CCS	US$/kW[1]	545	545	545	545	545	New gas to hydrogen plant with CCS. Methane steam reforming.
Liquids|Biomass|w/ CCS|1	US$/kW[1]	1,275	1,275	1,275	1,275	1,275	New biomass to liquids plant with CCS. Conventional ethanol and sugar plant.
Liquids|Biomass|w/ CCS|2	US$/kW[1]	1,865	1,865	1,865	1,865	1,865	New biomass to liquids plant with CCS. Advanced ethanol and sugar plant.
Liquids|Biomass|w/ CCS|3	US$/kW[1]	4,783	4,783	4,783	4,783	4,783	New biomass to liquids plant with CCS. Diesel production through Biomass-to-Liquids.
Liquids|Biomass|w/o CCS|1	US$/kW[1]	1,250	1,250	1,250	1,250	1,250	New biomass to liquids plant with CCS. Conventional ethanol and sugar plant.
Liquids|Biomass|w/o CCS|2	US$/kW[1]	1,840	1,840	1,840	1,840	1,840	New biomass to liquids plant with CCS. Advanced ethanol and sugar plant.
Liquids|Biomass|w/o CCS|3	US$/kW[1]	4,156	4,156	4,156	4,156	4,156	New biomass to liquids plant with CCS. Diesel production through Biomass-to-Liquids.
Liquids|Biomass|w/o CCS|4	US$/kW[1]	2,417	2,417	2,216	2,014	1,813	New biomass to liquids plant with CCS. Kerosene production through HEFA.
Liquids|Biomass|w/o CCS|5	US$/kW[1]	1,884	1,884	1,727	1,570	1,413	New biomass to liquids plant with CCS. Kerosene production through Biomass-to-Liquids.
Liquids|Biomass|w/o CCS|6	US$/kW[1]	210	210	210	210	210	New biomass to liquids plant w/o CCS. Biodiesel production with methanol.
Liquids|Biomass|w/o CCS|7	US$/kW[1]	210	210	210	210	210	New biomass to liquids plant w/o CCS. Biodiesel production with ethanol.
Liquids|Oil|1	US$/kW[1]	1,260	1,260	1,260	1,260	1,260	New oil refinery. Premium-style.
Liquids|Oil|2	US$/kW[1]	3200	3200	3200	3200	3200	New oil refinery. Small scale diesel refinery.
Liquids|Oil|3	US$/kW[1]	4,400	4,400	4,400	4,400	4,400	New oil refinery. Small scale gasoline refinery.
Liquids|Oil|4	US$/kW[1]	3,000	3,000	3,000	3,000	3,000	New oil refinery. Small scale kerosene refinery.
Transportation|LDV|BEV|1	US$/vehicle	95,000	95,000	95,000	95,000	95,000	New battery electric (BE) light duty vehicle (LDV). Battery electric.
Transportation|LDV|BEV|2	US$/vehicle	55,000	55,000	55,000	55,000	55,000	New battery electric (BE) light duty vehicle (LDV). Hybrid vehicle.
Transportation|LDV|BEV|3	US$/vehicle	61,000	61,000	61,000	61,000	61,000	New battery electric (BE) light duty vehicle (LDV). High efficiency hybrid vehicle.
Transportation|LDV|BEV|4	US$/vehicle	75,000	75,000	75,000	75,000	75,000	New battery electric (BE) light duty vehicle (LDV). Plug-in hybrid vehicle.
Transportation|LDV|FC	US$/vehicle	100,000	100,000	100,000	100,000	100,000	New hydrogen fuel cell (FC) light duty vehicle (LDV).
Transportation|LDV|ICE|1	US$/vehicle	18,000	18,000	18,000	18,000	18,000	New internal combustion engine (ICE) light duty vehicle (LDV). Standard gasoline.
Transportation|LDV|ICE|2	US$/vehicle	24,000	24,000	24,000	24,000	24,000	New internal combustion engine (ICE) light duty vehicle (LDV). High efficency gasoline.

Transportation|LDV|ICE|3	US$/vehicle	13,000	13,000	13,000	13,000	13,000	New internal combustion engine (ICE) light duty vehicle (LDV). Standard ethanol.
Transportation|LDV|ICE|4	US$/vehicle	18,000	18,000	18,000	18,000	18,000	New internal combustion engine (ICE) light duty vehicle (LDV). Standard flex-fuel.
Transportation|LDV|ICE|5	US$/vehicle	240,000	240,000	240,000	240,000	240,000	New internal combustion engine (ICE) light duty vehicle (LDV). High efficency flex-fuel.
Transportation|LDV|ICE|6	US$/vehicle	20,000	20,000	20,000	20,000	20,000	New internal combustion engine (ICE) light duty vehicle (LDV). Standard natural gas
Transportation|LDV|ICE|7	US$/vehicle	26,000	26,000	26,000	26,000	26,000	New internal combustion engine (ICE) light duty vehicle (LDV). High efficency natural gas.

Note: [1] per unit of main output.