




# Brazil's emission trajectories in a well-below 2 °C world: the role of disruptive technologies versus land-based mitigation in an already low-emission energy system

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Received: 27 October 2017 / Accepted: 30 August 2020 / Published online: 2 October 2020  
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## Abstract

The Nationally Determined Contributions (NDCs) to the Paris Agreement (PA) submitted so far do not put the world on track to meet the targets of the Agreement and by 2020 countries should ratchet up ambition in the new round of NDCs. Brazil's NDC to the PA received mixed reviews and has been rated as “medium” ambition. We use the Brazil Land Use and Energy System (BLUES) model to explore low-emission scenarios for Brazil for the 2010–2050 period that cost-effectively raise ambition to levels consistent with PA targets. Our results reinforce the fundamental role of the agriculture, forest, and land use (AFOLU) sectors and explore inter-sectoral linkages to power generation and transportation. We identify transportation as a prime candidate for decarbonization, leveraging Brazil's already low-carbon electricity production and its high bioenergy production. Results indicate the most important mitigation measures are electrification of the light-duty vehicle (LDV) fleet for passenger transportation, biodiesel and biokerosene production via Fischer-Tropsch synthesis from lignocellulosic feedstock, and intensification of agricultural production. The use of carbon capture and storage (CCS) as well as netzero deforestation make significant contributions. We identify opportunities for Brazil, but synergies and trade-offs across sectors should be minded when designing climate policies.

**Keywords** Brazil emissions · Climate mitigation · Bioenergy and biofuels · Low-carbon transition · Mitigation scenarios · Integrated assessment model

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This article is part of a Special Issue on “National Low-Carbon Development Pathways” edited by Roberto Schaeffer, Valentina Bosetti, Elmar Kriegler, Keywan Riahi, Detlef van Vuuren, and John Weyant

**Electronic supplementary material** The online version of this article (<https://doi.org/10.1007/s10584-020-02856-6>) contains supplementary material, which is available to authorized users.

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## 1 Introduction

The Paris Agreement-PA (UNFCCC 2015) shifted emphasis of climate negotiations from a top-down global approach to one in which countries make voluntary pledges called Nationally Determined Contributions (NDCs). Still, the NDCs submitted do not put the world on track to meet the targets of the Agreement (Rogelj et al. 2016) and by 2020 countries should ratchet up ambition in the new round of NDCs and submit their mid-century strategies (MCSs).

However, climate action must be framed in the context of other societal objectives such as those embodied in the United Nations' *Agenda 2030* and the Sustainable Development Goals (SDGs) (Krey et al. 2019b; von Stechow et al. 2016). Concurrent attainment of the 17 SDGs requires an integrated approach that accounts for interlinkages between SDGs, maximizing synergies and minimizing trade-offs in policy design and implementation (Nilsson et al. 2018; Rogelj et al. 2018). The IPCC Special Report on 1.5 Degrees (SR15) (Roy et al. 2018) found SDG 13 (Climate Action) to have strong linkages to other SDGs.

Brazil's NDC to the PA (GofB 2015a) received mixed reviews as to its ambition. The absolute targets of 1.3 Gt CO<sub>2</sub>eq for 2025 and 1.2 Gt CO<sub>2</sub>eq for 2030 were rated as "medium" ambition, at the "least ambitious level of a fair contribution" (CAT 2017; Pan et al. 2017). The Agriculture, Forests and Land Use (AFOLU) sector is the cornerstone of the Brazilian NDC and includes the Low-carbon Agriculture Plan (ABC Plan) reduction targets of between 133.9 and 162.9 Mt CO<sub>2</sub>eq, mostly through livestock sustainable intensification measures. The NDC also pledges to end illegal deforestation in Brazil. Targets in other sectors are weak or vague (Escobar 2015; Köberle et al. 2015). Energy targets include higher shares of renewable sources in primary energy mix and in power generation, to reach 45% and 33%, respectively, over 2005 levels by 2030, and also a vaguely defined energy efficiency improvement of 10% by the same date (GofB 2015a).

Brazil's total greenhouse gases (GHG) emissions have been stable around 1.5 Gt CO<sub>2</sub>eq since 2009 (SEEG 2019). Roughly speaking, agriculture, energy, and land use (deforestation) each account for about one-third of total GHG emissions on average in Brazil (GofB 2015b; SEEG 2019). Agriculture emissions are dominated by methane from enteric fermentation and nitrous oxide from synthetic fertilizers and animal wastes, energy emissions come mostly from the transportation sector and industry, and land use emissions are mostly CO<sub>2</sub> from land use change (LUC) (GofB 2015b). Power generation is already low-carbon, relying mostly on hydropower (~65%) and combustion of sugarcane bagasse and other biomass (~8%), and primary energy consumption (PEC) in the country is currently from roughly 45% low-carbon sources (EPE 2019). See SOM for more details.

Potential measures for emission abatement in agriculture include recuperation of degraded pastures (Assad et al. 2015; Strassburg et al. 2014) and integrated crop–livestock–forestry (iCLF) systems (Agroicone 2016; Balbino et al. 2011), which can lead to an increase in biomass and soil organic carbon (SOC), thereby reducing emissions and potentially, in some cases, making the process a GHG-emission sink for a period of 10–20 years (Carvalho et al. 2014, 2009; Cohn et al. 2014) and enable higher sustainable stocking rates, potentially sparing land for food, fiber, and biofuel production (Cardoso et al. 2016; De Oliveira et al. 2013). Tradeoffs include higher demands for energy (mostly diesel) and fertilizers, important sources of GHG emissions. Emissions from land use can be reduced mainly by eliminating deforestation (Rochedo et al. 2018), the main source of GHG emissions in Brazil until recently (MCTIC 2016; SEEG 2019).

Options for abatement of energy emissions include the use of wind and solar as well as bioelectricity with and without CCS for electricity generation, and the use of liquid biofuels in the transportation sector, especially replacing diesel for freight and kerosene for air transportation. The introduction of CCS in ethanol production also has the potential to contribute (Szklo et al. 2017). Alternatively, introduction of electric vehicles (EVs) could take advantage of the low-carbon electricity in the country, but this could reduce the role of ethanol, with effects on electricity generation from sugarcane bagasse (see SOM).

Producing biomass feedstock for bioenergy production could raise demand for land, with implications for agriculture and land use (Rathmann et al. 2012). In contrast, electrification of transportation in Brazil and worldwide could reduce demand for biofuels but increase demand for electricity with implications for the power sector. This interplay between AFOLU and energy sectors responds to varying degrees of GHG emission restrictions (see Methods). Therefore, it is critical to examine such trade-offs explicitly. Moreover, impacts on AFOLU sectors have implications for various SDGs, especially those dealing with food security (SDG2), water (SDG6), and biodiversity (SDGs 14 and 15).

We use the BLUES<sup>1</sup> model (IAMC 2020; Köberle 2018; Rochedo et al. 2018) to explore these linkages and to produce emission scenarios for Brazil for the 2010–2050 period, consistent with global efforts to stay within various temperature targets, comparing them with the Brazilian NDC.

The next section introduces the BLUES model and describes the scenarios. Section 3 shows results of key variables, contrasting them across scenarios. Section 4 discusses results focusing on the transportation sector's role as mediator of inter-sectoral linkages and on implications for the SDGs. Section 5 provides conclusions and key findings. Details on current trends and context in Brazil as well as additional analysis on results are provided in the SOM.

## 2 Methods

### 2.1 The BLUES model

The BLUES model is the most recent version of a family of models built on the MESSAGE model platform (Keppo and Strubegger 2010). It was developed for the Brazilian energy system and has been sequentially updated and applied to assess issues relevant to the national reality (see SOM for a detailed description). The model has recently been reconfigured for better detailing of both regional breakdown and endogenous energy efficiency and GHG mitigation options in the end-use sectors (Köberle 2018; Rochedo et al. 2018; Szklo et al. 2018). More recently, a representation of the land-use system (forests, savannas, low- and high-capacity pastures, integrated systems, cropland, double cropping, planted forests, protected areas) was introduced (Köberle 2018; Rochedo et al. 2018), along with a suite of advanced biofuel technologies not present in previous versions. In addition, the cost assumptions on electric vehicles and photovoltaic (PV) solar power have been updated to reflect recent developments.

As a perfect-foresight cost-minimization model, BLUES produces the least-cost pathway to meet emission budgets subject to constraints to reflect socioenvironmental conditions, policies,

<sup>1</sup> Brazil Land Use and Energy System model (aka COPPE-MSB\_v2.0). For documentation on the BLUES model see [https://www.iamcdocumentation.eu/index.php/Model\\_Documentation\\_-\\_BLUES](https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_BLUES)

and other limiting factors. The expansion of key technologies was constrained in the model to reflect technoeconomic restrictions to the deployment of new facilities, such as industrial capacity to manufacture equipment, skilled labor to build and operate the plants, and availability of capital to fund them (see SOM Section 1.2). Innovative biofuel production routes with and without CCS were constrained following this rationale. More details about the BLUES model can be found in the SOM.

## 2.2 The scenarios

### 2.2.1 Socioeconomic premises and reference scenario

The scenarios explored here are based on Shared Socioeconomic Pathway 2 (SSP2) assumptions (Fricko et al. 2017; Riahi et al. 2017), meaning that they do not include structural socioeconomic changes from historical trends in Brazil. GDP growth rates for Brazil were updated from SSP2 projections (Dellink et al. 2017) to reflect the near-term 2010–2020 growth rates (Köberle et al. 2018). The Reference scenario (*Ref*) in this study includes the most relevant public policies in effect in the country today which may impact GHG emissions. These include non-climate policies such as biofuel blending mandates and renewable energy auctions, and climate policies that are already under implementation such as the ABC Plan (MAPA 2012). Most of the mitigation measures included in the Brazilian NDC (GofB 2015a) are already in effect today through existing policies (Köberle et al. 2015). Table S1 shows the policies implemented in the construction of the scenarios described here.

The *Ref* scenario also includes an assumption of full implementation of the 2012 Forest Code via forcing net-zero deforestation post-2030, as compliance with the Code requires afforestation on some 30 Mha (Soares-filho et al. 2014). Finally, EV costs are projected to reach cost parity with conventional vehicles by 2040. Although EV cost parity by 2040 may seem overly conservative given recent developments (BNEF 2017), the lack of structural socioeconomic changes may imply light-duty vehicles (LDVs) in the country will continue to cost more than they do abroad. Thus, since there are currently no policies to incentivize EVs, we assume the country will lag behind global cost developments by about a decade. This also applies to electric trucking, which faces the additional barriers from deficient infrastructure in the country in the form of badly maintained roads and an unreliable electricity grid. For this reason, electric trucks are not included in the options available to the model.

### 2.2.2 Climate policy scenarios

Three climate mitigation scenarios explore progressively more stringent emission constraints based on the current policy scenario (*Ref*) with various emissions constraints, including two early-action scenarios (mitigation from 2020) and one delayed-action scenario (from 2030). Two scenarios are consistent with global efforts to stay below 2 °C average temperature rise above pre-industrial levels: one early-action (*2 deg*) and one delayed-action scenario in which mitigation begins only after following the *Ref* trajectory through 2030 (*2deg\_dly*). Finally, the third scenario is a 1.5 °C scenario (*1p5deg*) that assumes early-action consistent with Brazil's contribution to a global 1.5 °C target (Kriegler et al. 2019).

The climate mitigation scenarios were implemented via emissions budgets, as described in detail in the SOM. We apply resulting mid-century budgets for Brazil's share of a global 1000 Gt of CO<sub>2</sub> (consistent with a > 66% chance of staying within 2 °C) and 400 Gt of CO<sub>2</sub> (in

line with a > 66% chance of staying within 1.5 °C warming limit by 2100), taken from cost-optimal global runs of the COFFEE model (Rochedo 2016; Rochedo et al. 2018; Roelfsema et al. 2020) for each of the temperature targets. The COFFEE model is a global integrated assessment model (IAM) built on the same platform as BLUES and having a similar structure, in which Brazil is represented as a single region in a world comprised of 18 regions (see SOM). Because COFFEE runs through 2100 and BLUES only through 2050, the COFFEE cumulative emission budgets for 2010–2050 were used. The COFFEE model was chosen for several reasons. First, it is built on the same modeling platform as BLUES and follows a similar logic and structure. Second, it has one of the best sectoral representations of Brazil among all the IAMs since it was built to explicitly represent Brazil's role in the world and many IAMs do not even have Brazil represented as separate from Latin America (see Section S1.3.2).

The 2010–2050 budgets implemented in BLUES were as follows: 23.6 Gt CO<sub>2</sub>, for the *2 deg* and *2deg\_dly* scenarios and 15.4 Gt CO<sub>2</sub> for the *1p5deg* scenario. These emission budgets represent about 15 years of the country's 2010 emissions for the 2 °C scenarios and about 10 years for the 1.5 °C scenarios. The budgets were implemented in BLUES as a cap on cumulative CO<sub>2</sub> emissions and, to limit emissions of non-CO<sub>2</sub> GHGs, these were priced at GWP-AR4 equivalency<sup>2</sup> starting in 2020, as explained in SOM Section S2. The resulting budgets are close to the median from other IAMs for Brazil (see Section S1.3.2). For more details on the scenario protocols used in this paper see Schaeffer et al. (2020, this issue).

### 3 Results

Results indicate key linkages between AFOLU, transportation, and energy sectors. They point to the fundamental role of AFOLU in Brazil's mitigation efforts, with its emissions becoming negative before those of the energy sector. Intensification of livestock contributes significantly to AFOLU CO<sub>2</sub> abatement in BLUES, thereby increasing the currently low stocking rate of Brazilian pastures. In fact, this occurs even in the absence of emissions constraints, which is explained by the low or negative abatement cost of this measure, its large potential, and continuing implementation of the ABC Plan<sup>3</sup> (MAPA 2012). Introduction of iCLF systems makes important contributions to improve yields.

As mitigation targets become more stringent (tighter CO<sub>2</sub> budgets), technological shifts further decarbonize sectors with remaining mitigation potential. In the energy sector, mitigation measures include low-carbon sources for all energy carriers, fuel switch in transportation, and energy efficiency in industry and transportation, along with transitions to low-carbon power generation from biomass, wind and solar.

The transportation sector stands out as having a significant potential for emission reductions through the use of biofuels, with and without CCS,<sup>4</sup> and the electrification of the LDV passenger fleet. Introduction of EVs in budget scenarios leads to higher electricity consumption, affecting power generation expansion strategies the mix of biofuel production, also impacting the agricultural sector.

<sup>2</sup> The energy module in BLUES was built prior to the release of GWP-AR5 values.

<sup>3</sup> The model results provide evidence to the economic advantage of intensifying livestock production in Brazil. However, several market barriers (as identified by Gil et al. (2015) and Köberle et al. (2017)) still hamper large-scale adoption in the country.

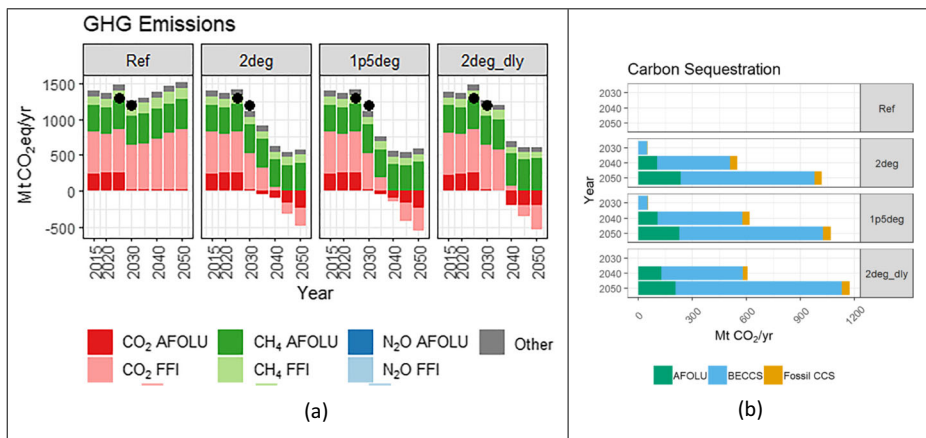
<sup>4</sup> CCS here is applied in the production phase of the biofuel, not in the transportation sector per se.

We explore these dynamics in the following sections and offer deeper analyses in the discussion section.

### 3.1 Emissions

Figure 1a shows resulting GHG emission trajectories in each scenario. Emission reductions in budget scenarios result mainly from reductions in CO<sub>2</sub> emissions with some contribution from CH<sub>4</sub> and N<sub>2</sub>O reductions in the short-term. Emissions of both CH<sub>4</sub> and N<sub>2</sub>O drop in the short-term but return to 2015 levels by the end of the period due to increased activity of their sources, mainly in the AFOLU sectors. One distinct aspect of Brazil's emission profile is the high share of non-CO<sub>2</sub> gases, particularly CH<sub>4</sub> and N<sub>2</sub>O from AFOLU sectors. Across budget scenarios emissions of non-CO<sub>2</sub> gases dominate towards 2050, as net CO<sub>2</sub> emissions become negative. The effect of the net-zero deforestation assumption is clear by the sudden drop in AFOLU CO<sub>2</sub> emission post-2030, highlighting the impact that full implementation of the Forest Code can have on the country's climate action.

Brazil's GHG emission targets pledged in the NDC are shown as black dots in Fig. 1a. Some key insights can be drawn from this figure: (i) the *Ref* scenario shows current policies are only partially in line with NDC targets and that strengthening of ambition may be required for the country to meet its 2030 emissions target; (ii) policies helping Brazil to meet its NDC would put the country within a trajectory consistent with a least-cost, global end-of-century 1.5 °C target in 2025, but the 2030 target would need to be strengthened; and (iii) delayed-action to 2030 would imply drastic measures towards 2040 in order to bring the country closer to a cost-optimal trajectory to a well-below 2 °C global target. These insights should contribute to Brazil's development of its mid-century strategy for climate action.



**Fig. 1** GHG emission trajectories 2015–2050 (a) and CO<sub>2</sub> sequestration post-2030 (b). FFI fossil fuel and industry. The black dots indicate the NDC pledged targets. The category “Other” includes GHG sources not modeled in BLUES. They are dominated by indirect nitrous oxide emissions but also include emissions of hydrofluorocarbons (HFCs), methane from livestock other than cattle and poultry, and nitrous oxide from organic soils. The value for 2010 from GoB (2015b) and are assumed constant throughout the period



### 3.2 Carbon sequestration

Figure 1b shows that long-term reductions in CO<sub>2</sub> emissions in Brazil can be achieved mainly through a combination of AFOLU efforts and deployment of CCS technologies in the energy sector. Brazil's large biofuels potential (Smeets and Faaij 2010) and the availability of sequestration sites (Rochedo et al. 2016) mean it can deploy significant levels of bioenergy with CCS (BECCS<sup>5</sup>) to help further decarbonize its economy. The figure shows total CO<sub>2</sub> sequestered and through which measure and is not limited to carbon removal from the atmosphere.

AFOLU sequestration is the aggregate result of (i) intensification of livestock production, via conversion of low-capacity pastures to high-capacity pastures and integrated systems, and (ii) afforestation via growth in planted forests and regrowth of natural forests (see Section 3.3). There is more BECCS in the late-accession *2deg\_dly* than in the *1p5deg* scenario due to the shorter time period available to decarbonize.

Negative CO<sub>2</sub> emissions in Fig. 1a come from contributions of energy-sector CCS and AFOLU sequestration (Fig. 1b). BECCS becomes increasingly important as the mitigation challenges become tougher. Carbon capture occurs in electricity generation and also in the production of ethanol, BTL-kerosene and BTL-diesel (Tagomori 2017; Tagomori et al. 2019), used to decarbonize the transport sector. CO<sub>2</sub> capture in the fermentation phase of ethanol production is a result we have reported elsewhere (Herrerias-Martínez et al. 2015; Koberle et al. 2015), an important mitigation option for Brazil (see Section 3.6). BECCS deployment in the *1p5deg* and *2deg\_dly* scenarios reaches cumulative sequestration of around 2.2 Gt of CO<sub>2</sub> by 2050.

It must be said that negative emissions can be costly in energy and economic terms, and very clear governance protocols would need to be in place to account for sequestered CO<sub>2</sub> (Gough et al. 2018; Peters and Geden 2017). Although CCS costs are currently high, they are projected to fall in the medium- to long-term (Budinis et al. 2018). In addition, carbo-duct networks would need to be built to carry captured CO<sub>2</sub> to injection sites, adding to the governance issues surrounding CCS (Merschmann et al. 2016; Tagomori et al. 2018). Policies to support and regulate CCS in Brazil are lacking (da Costa 2014).

### 3.3 Land use and land use change

As mentioned before, AFOLU sectors play an important part in Brazil's mitigation effort. Land use change (LUC) from 2015 across scenarios is shown in Fig. 2. Results show that intensification of livestock causes significant reduction in low-capacity pasture area, which is transformed into high-capacity pastures (with average stocking rates twice as high), integrated systems and cropland. This holds across all scenarios, including current policies, where a reversal of the growth trend of low-capacity pastures indicates this as an attractive measure even in the absence of climate policies, in line with increasing interest in such systems given their demonstrated potential for higher profitability (De Oliveira et al. 2013). The steep changes in pasture area from low-capacity to high-capacity in Fig. 2 are equivalent to a conversion of about 50 Mha in 30 years, a little more than 1.5 Mha per year. This is not unprecedented. A transition at this rate and scale has occurred before in Brazilian agricultural

<sup>5</sup> BECCS is understood to include both bioelectricity generation and bioliquids production with CCS.

production systems. Between 1992 and 2012, no-till agriculture spread across some 30 Mha and is today used in more than 50% of grain area in the country (Inagaki et al. 2016).

To meet the demands for food, fiber, and energy, about 12 Mha of low-capacity pastures are converted to high-capacity in the *Ref* scenario, indicating current trends will almost meet the stated NDC goal of 15 Mha. On the other hand, there is an increase of only 0.2 Mha hectares of integrated systems, well short of the 4 Mha pledged in the NDC. Likewise, the 0.5 Mha of planted forests fall short of the target for additional 4 Mha. Cultivated land increases while natural lands decrease in the short-term and slightly recover post-2035 in mitigation scenarios. Table S1 shows area changes in 2050 relative to 2010 for each land cover type in Fig. 2. Across all scenarios, agricultural land (crops and livestock) peaks between 2025 and 2030 at around 295 Mha. In the *Ref* scenario, converted lands do not return to their original cover by 2050. However, as the budgets become more stringent, intensification of agriculture drives the conversion of low-capacity pastures to high-capacity pastures and integrated systems, reducing total area devoted to livestock production.

Abandoned pastureland is converted to cropland and planted forests or left to regrow with natural vegetation, especially tropical forests (strong carbon sinks). By diminishing demand for land, agricultural intensification allows forests to recover significant shares of lost area. Savannas recover much less because of their lower carbon stock, implying further losses to the biodiversity-rich *Cerrado* biome. In the *2deg\_dly* scenario by 2050, roughly the same extent of forest area converted to agricultural use (~6 Mha) since 2015 is returned to natural forests (afforestation) (Fig. S8).

### 3.4 Primary energy

The continuing growth trend in PEC is clearly reflected in the *Ref* scenario, with increases across the range of currently-used energy sources (Fig. 3a). In the budget scenarios, (lignocellulosic) biomass and sugarcane increasingly replace oil and coal as emission

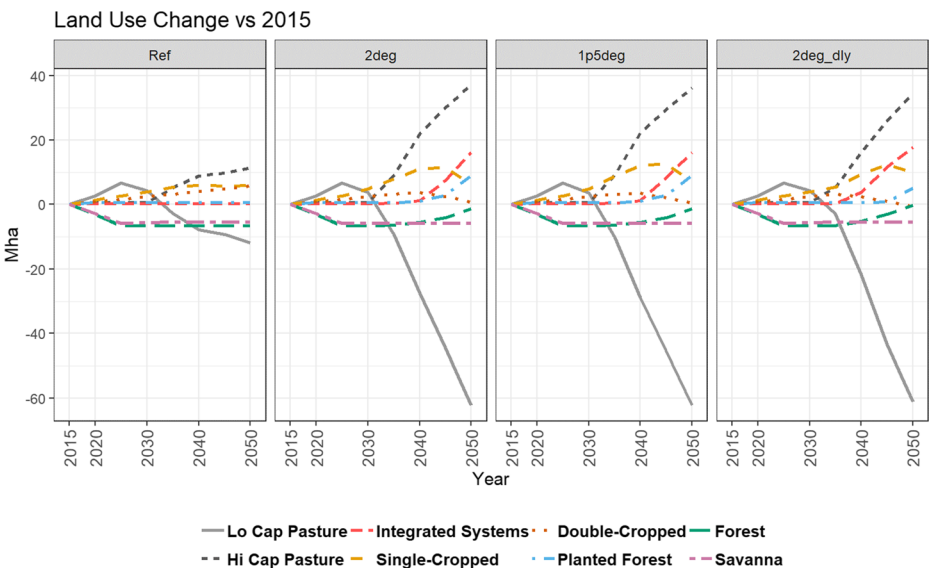
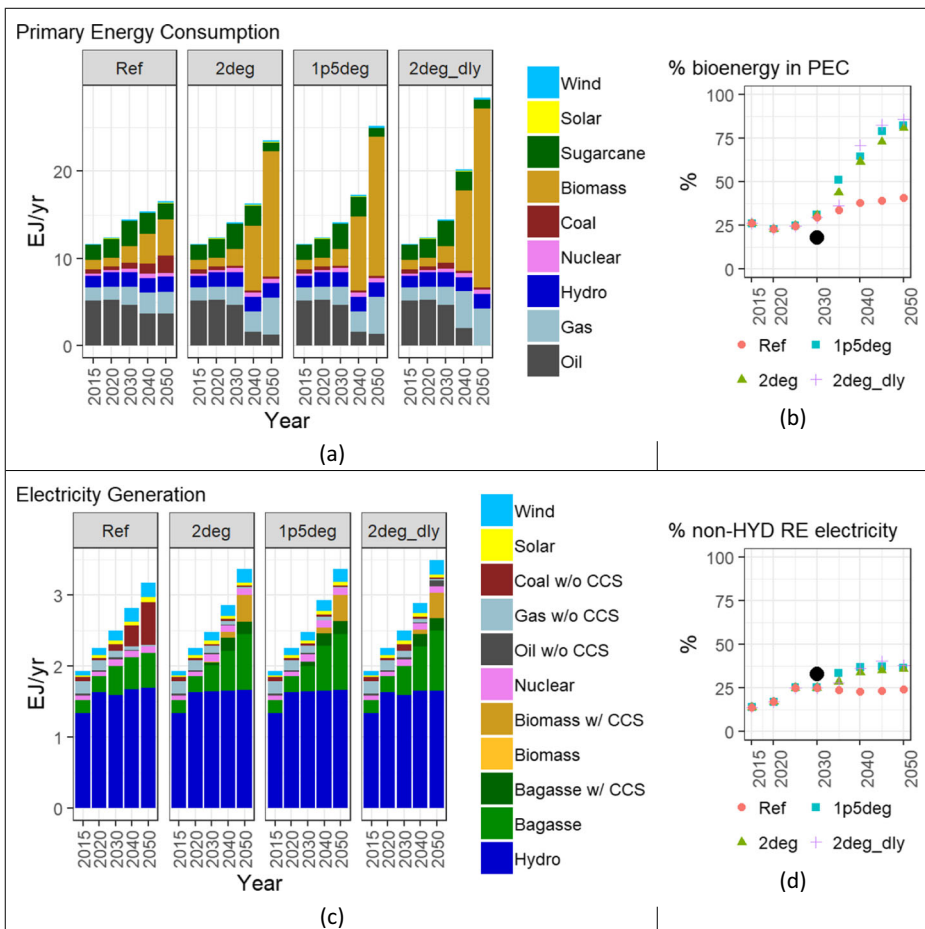


Fig. 2 Land use change compared with 2010 across scenarios



constraints become tighter. In the most stringent cases (*1p5deg* and *2deg\_dly*), coal virtually disappears and oil consumption drops by more than 80% (completely disappearing in *2deg\_dly*), forcing the refining sector to adjust. Biomass share grows to scenario-dependent 50–75% of total PEC by 2050, with profound impacts on land demand for bioenergy, which helps explain some of the land-use dynamics described in Section 3.3 (see Section 4).

Competition between biomass and sugarcane is largely determined by assumptions for their respective techno-economic parameters. In the current version of BLUES, biomass production from grasses stands out as the least-cost feedstock source for biofuels production via biomass-to-liquids Fischer-Tropsch (BTL-FT) synthesis of biodiesel and biokerosene. However, BTL-FT synthesis is currently non-existent in Brazil, meaning this novel technology is deployed gradually, ramping up capacity at a rate commensurable with industrial capacity (SOM Section S1.2.2). Figure 3b shows this growth of bioenergy, which reaches between 65 and 80% share of PEC in 2050 across budget scenarios. Additionally, the NDC target of 33% bioenergy in PEC is already met in the cost-optimal *Ref* scenario.



**Fig. 3** Primary energy consumption (PEC) (a), share of bioenergy in PEC (b), power generation (c), and share of non-hydro renewable energy in power generation (d) in Brazil. The black dots show the NDC targets for the plotted quantities

### 3.5 Power generation

Hydropower remains the mainstay of the Brazilian power system, but its share drops across all scenarios (Fig. 3c, d). In the absence of climate policies (*Ref*), coal power generation gains space after 2030 in this cost-optimization model, as it produces the lowest-cost electricity, in line with other baseline scenarios previously reported elsewhere (Köberle et al. 2015, 2018; Lucena et al. 2016; Portugal-Pereira et al. 2016). Nonetheless, wind, solar, and nuclear generation also see significant increases in the *Ref* scenario.

As emission constraints are introduced, bioelectricity increasingly pushes coal out of the energy mix. Coal-fired capacity is replaced in all budget scenarios by bioelectricity production with and without CCS, from both sugarcane bagasse<sup>6</sup> and other biomass feedstocks (Fig. 3c). A small amount of legacy coal-fired generation remains through 2050 from lignite mines in the South region of Brazil.

Counterintuitively, oil-fired generation without CCS enters the solution of budget scenarios, explained by the fact that diesel fuel is gradually decarbonized through blending of BTL-FT biodiesel, surpassing 70% of the diesel pool by 2050 (Section 3.6).

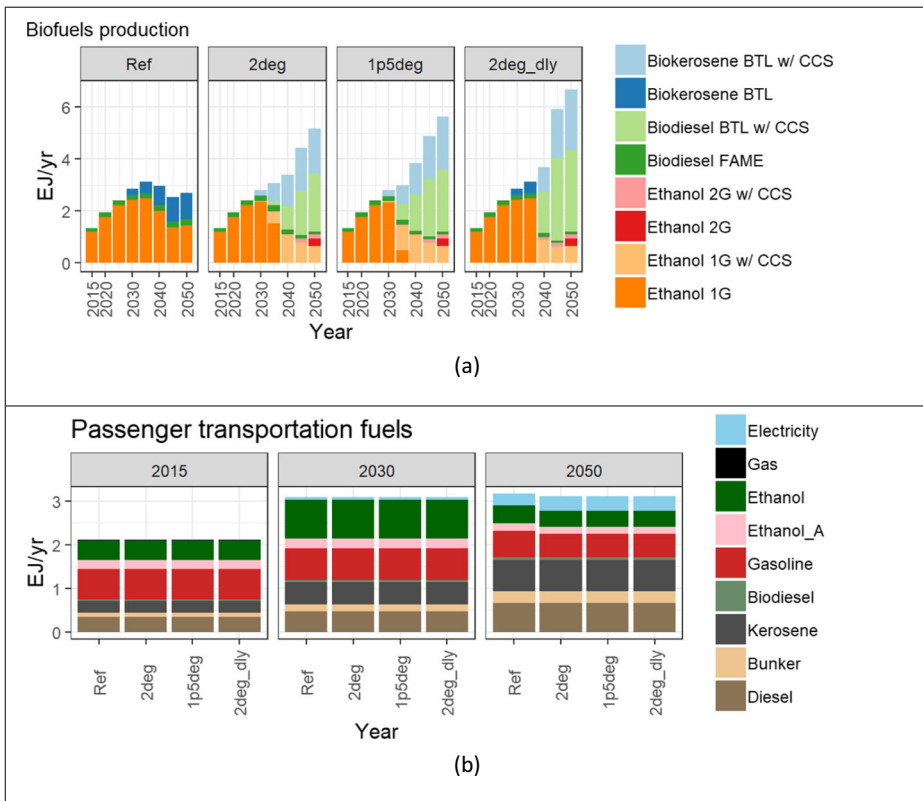
In addition, some competition occurs between biomass-fired electricity (mostly from bagasse and residues) and non-biomass renewables (hydro, solar, and wind). This results from the need for negative emissions in the long-term to compensate for higher emissions in the short-term, and so BECCS is used to both meet electricity demand and remove CO<sub>2</sub> from the atmosphere. All budget scenarios deploy large amounts of bioelectricity from sugarcane and lignocellulosic sources, with and without CCS. Bagasse is a by-product and has null cost, while biomass provides firm power which gives it the advantage of not requiring back-up capacity as is the case for intermittent sources. The budget scenarios also boast slightly higher electricity demand, spurred by the electrification of the LDV fleet (Section 3.7).

Nonetheless, non-biomass renewables grow in all scenarios. Wind power reaches levels comparable to today's bioelectricity production from bagasse (~0.2 EJ/year in 2050), and solar also grows. Brazil has potential for solar and wind exceeding the values deployed in these scenarios by BLUES (CEPEL 2013; Simioni and Schaeffer 2019), but the CCS option makes bioelectricity more attractive. As with any cost-optimization model, different cost and efficiency assumptions may yield different results, potentially tipping the scales in favor of wind and solar over bioelectricity. PV costs were updated to reflect recent developments, but the stringent emission constraints favor BECCS deployment. In spite of these increases, non-hydro renewables fail to meet the NDC target share of 33% of power generation.

### 3.6 Biofuels

Important changes happen in the biofuel sector as emission budgets tighten (Fig. 4a). The sharp increase in production in the stringent scenarios is driven by the need to decarbonize freight transportation and aviation. By 2050, ethanol and FAME biodiesel (1st Gen) production have peaked and returned to near 2015 levels. Importantly, most of the ethanol and advanced biofuels are produced with CCS in the production phase of the fuel, leveraging these low-cost options available to the model. Ethanol production decreases following increasing penetration of EVs in the LDV fleet.

<sup>6</sup> Sugarcane bagasse is the solid residue after sugarcane is crushed to extract the juice from which sugar and 1st generation ethanol are made.



**Fig. 4** Biofuels production (a) and passenger transportation fuel mix (b) deployed to meet energy services demand in Brazil. Ethanol\_A is anhydrous ethanol blended into gasoline at 27.5% by volume

BTL-diesel with CCS is used to decarbonize road freight transportation, by far the most important modal for freight in Brazil (EPE 2014). Production of advanced biofuels reaches high-enough levels to completely replace oil products in the *2deg\_dly* scenario by 2050, meaning both diesel and kerosene are low-carbon biofuels after 2030 since diesel fuel is gradually decarbonized by the blending of BTL-FT biodiesel, surpassing 64%, 69%, and 70% (*2 deg*, *1p5deg*, *2deg\_dly*, respectively) of the diesel pool by volume in 2050. The high share of BTL-diesel in diesel fuel also enables diesel engine busses to remain an option for passenger transportation throughout the period across scenarios. Interestingly, BTL-biojet fuel enters the mix in the *Ref* scenario, which is unexpected. The model chooses to deploy BTL technology instead of expanding the jetfuel capacity in refineries, which is currently limited in the country (Carvalho 2017). All scenarios have BTL-kerosene accounting for 100% of jetfuel demand as early as 2040, although in reality some technical limitations may preclude this.

### 3.7 Transportation

As global prices of hybrid (HYB), plug-in hybrid (HUYB), and electric vehicles (EV) are projected to drop in the short- to medium-terms, these become important alternatives to decarbonize passenger transportation using the country’s low-carbon electricity. Hybrid and EV costs are implemented in BLUES to reach parity with conventional cars by 2040. Thus,

starting in that year, the model switches to EVs in the light commercial category (mostly taxis), that is, the least efficient LDVs in the model delivering transportation services. The model also completely shifts from internal combustion engine (ICE) motorcycles to fully electric 2-wheelers starting in 2030 in all budget scenarios.

Figure 4b shows passenger transportation fuel mix across scenarios for modeled years 2015, 2030, and 2050 (for a similar figure for freight fuels, see Fig. S5). Growing demand for mobility services in Brazil is reflected by the growing energy demand of passenger transportation towards 2050.

In spite of higher EV penetration, flex fuel vehicles remain the most important private passenger transportation alternative, running mostly on a blend of 70% gasoline (containing 27.5% anhydrous ethanol) and 30% hydrated ethanol.<sup>7</sup> In all mitigation scenarios, electrification of the LDV fleet begins in 2035, with motorcycles and taxis replaced by their electric counterparts. The higher conversion efficiency of EVs causes a significant drop in energy consumption to meet passenger transportation services demand. On an energy basis, EVs account for 25% of passenger private transportation in 2050, increasing electricity demand with implications for power generation (Section 3.5), and reductions in ethanol and gasoline consumption. Implications of these results are addressed in depth in the discussion section (see also SOM Section 1.4.1).

Passenger public transport continues to be done by diesel ICE buses, but the increasing share of BTL-diesel in the fuel mix means emissions stabilize. Transportation emissions peak in 2030 and begin to drop as electricity and biofuels gain space in the energy mix of the sector. Total passenger emissions peak in 2030.

Stringent scenarios bring higher use of highly specified drop-in BTL biofuels,<sup>8</sup> produced with and without CCS (Section 3.6) and blended into the diesel and kerosene pools. This effectively makes diesel and kerosene low-carbon fuels, allowing them to maintain their share in the fuel mix of passenger transportation sector (Fig. 4b). The same occurs in freight transportation, where fuel types remains largely unchanged from the *Ref* scenario in 2050.

## 4 Discussion

Countries are currently preparing to submit revised NDCs in 2020, and the expectation is to ratchet up ambition to close the emissions gap and put the world on track to fulfill PA goals to curb climate change. In addition, Article 4 of the Agreement invited parties to submit, by 2020, long-term GHG emission strategies known as “mid-century strategies.” This paper examined how specific targets of the Brazilian NDC compare to current trends and to more ambitious scenarios to 2050 consistent with global efforts to limit climate change to well-below 2 °C compared with the pre-industrial era. Higher ambition was implemented in the BLUES model as tight emissions budgets equivalent to 15 years of the country’s 2010-level CO<sub>2</sub> emissions for a 2 °C global temperature target and to 10 years of 2010 emissions for a 1.5 °C global target. Although it can be argued that these targets go beyond what may be considered a fair

<sup>7</sup> Flex vehicles are modeled as operating in two modes: in option 1, the ratio gasoline/ethanol is 30/70, and in option 2 70/30. Option 2 dominates in all scenarios modeled here. Because BLUES models gasoline as blended with anhydrous ethanol at 27.5% by volume, average flex vehicle consumption is 50/50  $\{0.7 \cdot (1 - 0.275) = 0.5075\}$ .

<sup>8</sup> Drop-in biofuels are highly specified 2nd generation biofuels that can be injected directly into the fuel without any alteration of the engine.

contribution from Brazil under other effort-sharing allocation criteria (van den Berg et al. 2019, this issue), this allows exploration of the country's potential to ratchet up its contribution to the global effort under the PA.

Halting deforestation is the main challenge for Brazilian climate action. Full implementation of the Forest Code by 2030 implies afforestation on more than 30 Mha of land which, for the period of analysis, would more than compensate for deforestation pre-2030, effectively delivering on net-zero deforestation. Brazil already boasts a low-emissions energy system with high share of hydroelectricity in power generation and significant penetration of biofuels (ethanol and biodiesel) in liquid fuels. However, rising demand for energy services will drive expansion of energy supply capacity across sectors, which, in the *Ref* scenario, is met by increasing fossil fuel consumption. In the mitigation scenarios, the stringent constraints on emissions increase the value of negative emissions technologies (NETs), which include afforestation and BECCS in the current version of BLUES.

Our results suggest current policies in Brazil are only partially on track to meet the NDC. For AFOLU targets, the *Ref* scenario approaches the NDC target area for pasture recuperation by 2030 but falls short of the targets for integrated systems and planted forests, suggesting further action may be required. There is also only partial attainment of energy targets, with share of bioenergy well exceeding the 18% of PEC as pledged in the NDC, but the share of non-hydro renewables falling short of the 33% target by 2030. To further reduce the emissions intensity of Brazil's energy system, some innovative technologies are deployed at scale, especially in the livestock production (integrated systems) and biofuels (FT-BTL) sectors.

The agricultural sector can play a central role in Brazil's future in a low-carbon world. In the mitigation scenarios explored here, a revolution in livestock production leads to a shift towards high productivity livestock systems that break with the old expansionist approach that has driven deforestation in the past. Pasture recuperation and improved management can substantially increase livestock productivity, driving a shift from low- to high-capacity pastures as well as an increase in integrated crop-livestock-forestry systems (Figs. 2 and S7). This enables carbon sequestration not only in agricultural soils but also from forest area expansion (Fig. S8) and from the deployment of BECCS (Figs. 3 and 4a) which could make Brazil CO<sub>2</sub>-negative around 2040, despite non-CO<sub>2</sub> gases meaning the country remains a net GHG emitter through 2050 (Fig. 1). However, although agriculture intensification can spare land for regrowth of natural vegetation (afforestation) and bioenergy production, there is evidence that intensification of agriculture may also increase land rents which may lead to further expansion of the agricultural area, increasing deforestation (Nepstad et al. 2009; Rose et al. 2013).

In our results, the improved agricultural production techniques enable decarbonization of energy sectors via deployment of various forms of bioenergy, mainly sugarcane and lignocellulosic feedstocks. Sugarcane yields ethanol from its juice and bioelectricity from bagasse and both make large contributions in mitigation scenarios. Technical upgrades such as higher efficiency boilers in sugar and ethanol plants raise productivity and produce more electricity with less bagasse. This well-known potential efficiency improvement in Brazil is not realized today due to financial uncertainties but could be spurred with introduction of carbon revenues.

First generation ethanol from sugarcane peaks around 2030 and is present through 2050 across scenarios, albeit with CCS in mitigation scenarios. This form of BECCS-liquids begins as early as 2035 but is gradually reduced due to the introduction of 2<sup>nd</sup> generation ethanol (Fig. 4a) and electrification of the LDV fleet (Fig. 4b). A more substantial contribution from liquid biofuels comes in the form of biodiesel and biokerosene with and without CCS. The lack of mature options in freight and aviation

means decarbonization of these sectors relies on bioenergy (Section 3.7), mainly from FT-BTL routes using lignocellulosic feedstock.

These results point to important dynamics between (i) electrification of the LDV fleet, (ii) biofuels production and use, and (iii) land use intensification. Each has implications not only for each other but also for the country's emissions profile and for future development of its energy-infrastructure complex. This has repercussions all the way down to the primary energy level, as seen in Fig. 3. Decarbonizing the transportation sector gives rise to these inter-sector ripple effects in energy and AFOLU sectors. These linkages are mediated by the transportation sector via biofuels, which link the AFOLU, transportation, refining, and power generation sectors. For example, sugarcane ethanol is currently used for passenger vehicles while bagasse from crushed sugarcane is burned to generate CO<sub>2</sub>-neutral<sup>9</sup> electricity. This, coupled with large shares of hydropower, implies low-carbon electricity, which favors introduction of EVs as a mitigation option. However, higher share of EVs reduces demand for light liquid fuels, affecting the refining sector. These dynamics are subject to cost and efficiency assumptions and model results need to be interpreted with care. Nonetheless, it points to specific areas where well-designed policy can have positive impacts across sectors, reducing trade-offs and enhancing synergies.

Across budget scenarios, biodiesel supplies between 68 and 73% of diesel demand in 2050, meaning refineries still have to produce some fossil diesel from crude. Due to the nature of the refining process, refineries produce some gasoline when running for diesel production, unless expensive processing units are added. This gasoline byproduct comes at a null cost and is used in spite of stringent carbon budgets. Generally, if one of the oil products remains in high demand (due to low elasticity of substitution), refineries will still produce a basket of products at a minimum level at null cost, reducing potential mitigation from their alternatives. In these results, declining refinery activity also means the model must cover residual demand for maritime bunker fuel by importing heavy fuel oil.

Coupled with CCS, both bioelectricity and biofuels have the potential for significant negative emissions, which contribute to meeting the stringent emissions budgets explored in this study. As is the case with most IAMs, the value of BECCS in BLUES is driven by model structure and assumptions and also by what is not represented in the model such as governance structures, water use, or other advanced energy production routes such as power-to-liquids or power-to-hydrogen (Köberle 2019). The levels of BECCS deployment projected here will require proper governance of the whole bioenergy chain, from the production phase to final consumption and sequestration of captured CO<sub>2</sub>. Monitoring for land use and land use change emissions will need to be robust enough to prevent undesirable consequences from bioenergy feedstock production, especially with regard to prevention of deforestation, sustainable water use, and biodiversity conservation (Fajardy et al. 2019).

The dynamics described here have implications for the attainment of the SDGs. As noted in Section 3.3, cultivated area increases in the short-term at the expense of natural lands, especially in the biodiversity-rich *Cerrado* biome of central Brazil (savannas in BLUES). This implies more deforestation to meet demands for food, fiber, and bioenergy, with potential negative impacts on biodiversity. In mitigation scenarios, deforestation peaks between 2025 and 2030, and forests begin to recover some of the lost area post-2030 (Fig. S8). This indicates that PA targets may be consistent with nature conservation in the long run but pose serious

<sup>9</sup> Bioelectricity from sugarcane is the result of burning bagasse, a by-product of sugar or ethanol production. Because bagasse is in fact a residue of the main activity, emissions should be allocated to the other products.



threats to the attainment of SDGs by 2030, especially those related to land use, such as biodiversity (SDG 15) and food security (SDG2).

Intensification of agriculture and livestock has mixed impacts on SDGs. On the one hand, recuperation of degraded pastures may well have a positive net effect since a small addition of inputs (diesel and fertilizer) may raise productivity, potentially leading to land sparing. On the other, attaining higher yield for crops may have adverse effects through increased use of diesel and fertilizers—impacting emissions (SDG13) and water quality (SDG 14), as well as through the potential need to deploy genetically modified cultivars (through genetically modified organisms—GMOs)—with potentially adverse effects on biodiversity.

The net effects of climate mitigation on SDGs are uncertain and beyond the scope of the current analysis. However, for the case of Brazil, these results identify important indicators like forest area and fertilizer use that suggest challenges for the concurrent achievement of the PA and other sustainable development objectives. Such challenges can only be overcome through the implementation of well-designed policy that takes into account the cross-cutting and interrelated repercussions of individual measures.

Limitations of this study include uncertainty as to the assumptions in input parameters of the BLUES model (Krey et al. 2019a). However, the complex interactions between bioelectricity and other power generation options, biofuels, the transportation sector, land use, and agriculture restrict the benefit of simplistic sensitivity analyses on cost parameters. Indeed, understanding the effects of cost assumptions of the various technologies represented in the BLUES model requires careful design of scenarios to test the sensitivity of the results to the input assumptions of the model. Such a sensitivity analysis is beyond the scope of this study and is reported elsewhere (Köberle et al. 2018). Nonetheless, a discussion on sensitivity tests conducted during the design of the scenarios reported here can be found in [SOM Section S1.5](#).

## 5 Conclusions

This paper used the BLUES model to examine potential GHG mitigation options for Brazil in the context of the PA and SDGs. Results indicate that current policies are on track to only partially deliver the pledges in the Brazilian NDC by 2030, but additional policies to meet the NDC would also put the country on a least-cost pathway consistent with global efforts to attain PA objectives. Key measures include net-zero deforestation post-2030, sustainable intensification of agriculture, electrification of the LDV fleet, and decarbonization of freight transportation and aviation via advanced BTL biofuels production with and without CCS.

Results indicate key linkages between AFOLU, transportation, and energy sectors. They point to the fundamental role of AFOLU in Brazil's mitigation efforts, with its emissions becoming negative before those of the energy sector. Intensification of currently extensive agricultural practices allows for bioenergy feedstock production while curbing deforestation and, in some cases, even allowing for afforestation. Bioenergy production links the land use and agriculture sectors to the energy sectors, especially transportation and power generation. This implies successful mitigation policies relying on bioenergy would need to take a systemic view of the supply chain from the agricultural phase to final consumption and sequestration of combustion CO<sub>2</sub>.

Halting deforestation is the main challenge for Brazilian climate action and full implementation of the Forest Code implies net-zero deforestation through 2050. With no deforestation, the land area required to grow the feedstock comes from sustainable intensification of



agriculture, especially of livestock production. Recuperation of degraded pastures and introduction of integrated crop–livestock–forestry systems meet demand for agricultural products using less land, with the added benefit of reducing emissions relative to current practices.

In the energy sector, mitigation measures include low-carbon sources for all energy carriers, fuel switch in transportation, energy efficiency in industry and transportation, and transitions to low-carbon power generation from biomass, wind, and solar. Brazil's high bioenergy potential makes negative emissions through BECCS a realistic option. The transportation sector stands out as having a significant potential for emissions reductions through the use of biofuels, with and without CCS,<sup>10</sup> and the electrification of the LDV passenger fleet. Power generation is already low-carbon, meaning passenger transportation can be decarbonized through electrification. However, there are limited options to decarbonize freight transportation and aviation and these stand out as prime candidates for enhanced climate action in the country. To that end, results point to biodiesel and biokerosene made from lignocellulosic feedstock via FT synthesis as an optimal alternative.

These dynamics have mixed implications for the attainment of the SDGs. In mitigation scenarios, deforestation peaks between 2025 and 2030, and forests begin to recover some of the lost area post-2030. This indicates climate action in Brazil to be consistent with the SDGs in the long-run despite some short-term challenges up to 2030. The levels of BECCS deployment projected here will require proper governance of the whole bioenergy chain and monitoring for land use and land use change emissions will need to be robust enough to prevent undesirable consequences from bioenergy feedstock production. The interlinked, cross-sectoral measures explored here require a systems approach to policy design to minimize trade-offs and maximize synergies across sectors.

**Acknowledgements** The authors would also like to express their gratitude to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (National Scientific and Technological Development Council—CNPq) for the essential support given for this work to be carried out.

**Funding** This work is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 642147 (CD-LINKS).

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## References

Agroicone (2016) Cattle ranching intensification as a key role on sustainable agriculture expansion in Brazil. Sao Paulo: Agroicone, INPUT Project

<sup>10</sup> CCS here is applied in the production phase of the biofuel, not in the transportation sector per se.

- Assad E, Pavao E, Jesus M de, Martins SC (2015) Invertendo o sinal de carbono da agropecuária brasileira. Uma estimativa do potencial de mitigação de tecnologias do Plano ABC de 2012 a 2023. São Paulo, Brazil: Observatório ABC
- Balbino LC, Barcellos A d O, Stone LF (2011) Marco referencial: integração lavoura-pecuária-floresta. Embrapa, Brasília
- BNEF (2017) When Will Electric vehicles be cheaper than conventional vehicles?
- Budinis S, Krevor S, Dowell NM, Brandon N, Hawkes A (2018) An assessment of CCS costs, barriers and potential. *Energ Strat Rev* 22:61–81. <https://doi.org/10.1016/j.esr.2018.08.003>
- Cardoso AS, Berndt A, Leytem A, Alves BJR, de Carvalho, Carvalho I d NO, de Barros Soares LH, Urquiaga S, Boddey RM (2016) Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. *Agric Syst* 143:86–96. <https://doi.org/10.1016/j.agsy.2015.12.007>
- Carvalho F (2017) Evaluation of the Brazilian potential for producing aviation biofuels through consolidated routes. Federal university of Rio de Janeiro (UFRJ)
- Carvalho JLN, Cerri CEP, Feigl BJ, Piccolo MC, Godinho VP, Cerri CC (2009) Carbon sequestration in agricultural soils in the Cerrado region of the Brazilian Amazon. *Soil Tillage Res* 103:342–349. <https://doi.org/10.1016/j.still.2008.10.022>
- Carvalho JLN, Raucci GS, Frazao LA, Cerri CEP, Bernoux M, Cerri CC (2014) Crop-pasture rotation: a strategy to reduce soil greenhouse gas emissions in the Brazilian Cerrado. *Agric Ecosyst Environ* 183:167–175. <https://doi.org/10.1016/j.agee.2013.11.014>
- CAT (2017) Climate action tracker: Brazil [WWW document]. *Clim. Action Tracker*. URL <http://climateactiontracker.org/countries/brazil.html> (Accessed 6.15.17)
- CEPEL (2013) Atlas do Potencial Eólico Brasileiro. Brasil, Rio de Janeiro
- Cohn AS, Mosnier A, Havlik P, Valin H, Herrero M, Schmid E, O'Hare M, Obersteiner M (2014) Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. *Proc Natl Acad Sci U S A* 111:7236–7241. <https://doi.org/10.1073/pnas.1307163111>
- Costa IVL da (2014) PROPOSTA DE ESTRUTURA REGULATÓRIA PARA SEQUESTRO GEOLÓGICO DE CO2 NO BRASIL E UMA APLICAÇÃO PARA O ESTADO DO RIO DE JANEIRO. Federal University of Rio de Janeiro
- Oliveira P De, Freitas RJ, Kluthcouski J, Ribeiro AA, Adriano L, Cordeiro M, Teixeira LP, Augusto R, Castro D, Vilela L, Balbino LC (2013) Evolução de Sistemas de Integração Lavoura-Pecuária-Floresta (iLPF): estudo de caso da Fazenda Santa Brígida, Ipameri, GO
- Dellink R, Chateau J, Lanzi E, Magné B (2017) Long-term economic growth projections in the shared socioeconomic pathways. *Glob Environ Chang* 42:200–214. <https://doi.org/10.1016/j.gloenvcha.2015.06.004>
- EPE (2014) Consumo de Energia no Brasil Análises Setoriais. Rio de Janeiro, Brasil: Empresa de Planejamento Energético (EPE)
- EPE (2019) Balanço Energético Nacional. Empresa de Pesquisa Energetica (EPE)
- Escobar H (2015) Brazil's climate targets draw lukewarm reviews. *Sci Insid* <https://doi.org/10.1126/science.aad4637>
- Fajardy, M., Köberle, AC, Mac Dowell, N., Fantuzzi, A. BECCS deployment: a reality check. Grantham Briefing Paper Number 28. London, UK: Grantham Institute, Imperial College London. Available online at <https://www.imperial.ac.uk/media/imperial-college/granthaminstitute/public/publications/briefing-papers/BECCS-deployment—a-reality-check.pdf>
- Fricko O, Havlik P, Rogelj J, Klimont Z, Gusti M, Johnson N, Kolp P, Strubegger M, Valin H, Amann M, Ermolieva T, Forsell N, Herrero M, Heyes C, Kindermann G, Krey V, McCollum DL, Obersteiner M, Pachauri S, Rao S, Schmid E, Schoepp W, Riahi K (2017) The marker quantification of the shared socioeconomic pathway 2: A middle-of-the-road scenario for the 21st century. *Glob Environ Chang* 42: 251–267. <https://doi.org/10.1016/j.gloenvcha.2016.06.004>
- Gil J, Siebold M, Berger T (2015) Adoption and development of integrated crop-livestock-forestry systems in Mato Grosso, Brazil. *Agric Ecosyst Environ* 199:394–406. <https://doi.org/10.1016/j.agee.2014.10.008>
- GofB (2015a) Intended nationally determined contribution (INDC) towards achieving the objective of the UNFCCC. Brasília, Brasil: Presidência da República
- GofB (2015b) Terceira Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima. Brasília, Brasil: Ministério da Ciência, Tecnologia e Inovação (MCTI)
- Gough C, Garcia-Freites S, Jones C, Mander S, Moore B, Pereira C, Röder M, Vaughan N, Welfle A (2018) Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C. *Glob. Sustain.* 1, e5. <https://doi.org/10.1017/sus.2018.3>
- Herreras-Martínez S, Koberle A, Rochedo P, Schaeffer R, Lucena A, Szklo A, Ashina S, van Vuuren DP (2015) Possible energy futures for Brazil and Latin America in conservative and stringent mitigation pathways up to 2050. *Tech Forecasting Soc Chang*. <https://doi.org/10.1016/j.techfore.2015.05.006>

- IAMC (2020) Model documentation - BLUES [WWW document]. Common Integr. Assess. Model doc. URL [https://www.iamcdocumentation.eu/index.php/Model\\_Documentation\\_-\\_BLUES](https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_BLUES) (Accessed 7.1.20)
- Inagaki T, Sá JC, De Oliveira Ferreira A, Briedis C, Tivet F, Romaniw J (2016) Macroagregados como indicadores de qualidade em sistema plantio direto. *Rev plantio direto* 151:2–8
- Keppo I, Strubegger M (2010) Short term decisions for long term problems – the effect of foresight on model based energy systems analysis. *Energy* 2033–2042
- Köberle A (2018) Implementation of land use in an energy system model to study the long-term impacts of bioenergy in Brazil and its sensitivity to the choice of agricultural greenhouse gas emission factors. Federal University of Rio de Janeiro
- Köberle, A.C., 2019. The value of BECCS in IAMs: a review. *Curr Sustain Energy Rep* 6, 107–115. <https://doi.org/10.1007/s40518-019-00142-3>
- Koberle A, Portugal J, Branco DC, Szklo AS, Lucena AFP (2015) Assessing the potential for ethanol - fueled power generation as a flexible dispatchable option for firming intermittent sources in Brazil, in: V Encontro Latinoamericano de Economía de La Energía. International Association for Energy Economics (IAEE), Medellín, Colombia
- Köberle A, Rochedo P, Portugal-Pereira J, Szklo AS, de Lucena AFP, Schaeffer R (2015) Brazil Chapter, in: Spencer, T., Pierfedericci, R. (Eds.), *Beyond the numbers: understanding the transformation induced by INDCs. A Report of the MILES Project Consortium. IDDRI - MILES Project Consortium, Paris*, pp. 34–45
- Köberle AC, Tagomori IS, Portugal-Pereira J, Schaeffer R (2017) Policy case study: evaluation of the Plano ABC in Brazil. Deliverable for CD-LINKS project WP1
- Köberle AC, Garaffa R, Cunha SB, Rochedo PR, Lucena AF, Szklo A, Schaeffer R (2018) Are conventional energy megaprojects competitive? Suboptimal decisions related to cost overruns in Brazil. *Energy Policy* 122:689–700. <https://doi.org/10.1016/j.enpol.2018.08.021>
- Krey V, Guo F, Kolp P, Zhou W, Schaeffer R, Awasthy A, Bertram C, de Boer HS, Fragkos P, Fujimori S, He C, Iyer G, Keramidas K, Köberle AC, Oshiro K, Reis LA, Shoi-Tehrani B, Vishwanathan S, Capros P, Drouet L, Edmonds JE, Garg A, Gernaat DEHJ, Jiang K, Kannavou M, Kitous A, Kriegler E, Luderer G, Mathur R, Muratori M, Sano F, van Vuuren DP (2019a) Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. *Energy* 172:1254–1267. <https://doi.org/10.1016/j.energy.2018.12.131>
- Krey V, Riahi K, Hasegawa T, Luderer G, Poblete-Cazenave M, Parkinson S, Rafaj P, Vrontisi Z, Arvesen A, Fragkiadakis K, Fricko O, Fujimori S, Rogelj J (2019b) Implications of the Paris agreement for achieving the sustainable development goals. *Nat Clim Chang* submitted
- Kriegler E, Ueckerdt F, Luderer G, Schaeffer R, Chen W, Gi K, Iyer GC, Kejun J, Krey V, Mathur R, Oshiro K, Roelfsema M, Safonov G, Soest HL van, Vishwanathan SS, Vrontisi Z, Després J, Drouet L, Harmsen M, Koberle A, Vuuren D van, Bertram C, Bosetti V, Capros P, Edmonds J, Evangelpoulou S, Frank S, Fricko O, Fujimori S, Garg A, He C, Huppmann D, Kitous A, Li N, Potashnikov V, Rochedo P, Shekhar S, Stevanović M, Wang H, Baumstark L, Elzen M den, Höhne N, Jacobuta G, Riahi K (2019) Paris Agreement suggests deep collective CO2 emissions reductions in the seven largest greenhouse gas emitting regions by mid century. *Nat Clim Chang* under revi
- Lucena AFP, Clarke L, Schaeffer R, Szklo A, Rochedo PRR, Nogueira LPP, Daenzer K, Gurgel A, Kitous A, Kober T (2016) Climate policy scenarios in Brazil: A multi-model comparison for energy. *Energy Econ* 56: 564–574. <https://doi.org/10.1016/j.eneco.2015.02.005>
- MAPA (2012) Plano Setorial de Mitigação e Adaptação às Mudanças Climáticas para Consolidação da Economia de Baixa Emissão de Carbono na Agricultura – PLANO ABC. Brasília: Ministério da Agricultura, Pecuária e Abastecimento (MAPA)
- MCTIC (2016) Estimativas Anuais de Emissões de Gases de Efeito Estufa no Brasil. Brasília: Ministério da Ciência, Tecnologia, Inovação e Comunicação (MCTIC)
- Merschmann PR d C, Szklo AS, Schaeffer R (2016) Technical potential and abatement costs associated with the use of process emissions from sugarcane ethanol distilleries for EOR in offshore fields in Brazil. *Int J Greenhouse Gas Control* 52:270–292. <https://doi.org/10.1016/j.ijggc.2016.07.007>
- Nepstad D, Soares-Filho BS, Merry F, Lima A, Moutinho P, Carter J, Bowman M, Cattaneo A, Rodrigues H, Schwartzman S, McGrath DG, Stickler CM, Lubowski R, Piris-Cabezas P, Rivero S, Alencar A, Almeida O, Stella O (2009) The end of deforestation in the Brazilian Amazon—supporting online material (SOM). *Science* 326:1–28. <https://doi.org/10.1126/science.1182108>
- Nilsson M, Chisholm E, Griggs D, Howden-Chapman P, McCollum D, Messerli P, Neumann B, Stevance AS, Visbeck M, Stafford-Smith M (2018) Mapping interactions between the sustainable development goals: lessons learned and ways forward. *Sustain Sci* 13:1489–1503. <https://doi.org/10.1007/s11625-018-0604-z>
- Pan X, den Elzen M, Höhne N, Teng F, Wang L (2017) Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environ Sci Pol* 74:49–56. <https://doi.org/10.1016/j.envsci.2017.04.020>

- Peters GP, Geden O (2017) Catalysing a political shift from low to negative carbon. *Nat Clim Chang* 7:619–621. <https://doi.org/10.1038/nclimate3369>
- Portugal-Pereira J, Koberle A, Soria R, Lucena A, Szklo A, Schaeffer R (2016) Overlooked impacts of electricity expansion optimisation modelling: the life cycle side of the story. *Energy* 1–12. <https://doi.org/10.1016/j.energy.2016.03.062>
- Rathmann R, Szklo A, Schaeffer R (2012) Targets and results of the Brazilian biodiesel incentive program—has it reached the promised land? *Appl Energy* 97:91–100. <https://doi.org/10.1016/j.apenergy.2011.11.021>
- Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O, Lutz W, Popp A, Cuaresma JC, Samir KC, Leimbach M, Jiang L, Kram T, Rao S, Emmerling J, Ebi K, Hasegawa T, Havlik P, Humpenöder F, Da Silva LA, Smith S, Stehfest E, Bosetti V, Eom J, Gernaat D, Masui T, Rogelj J, Streffer J, Drouet L, Krey V, Luderer G, Harmsen M, Takahashi K, Baumstark L, Doelman JC, Kainuma M, Klimont Z, Marangoni G, Lotze-Campen H, Obersteiner M, Tabeau A, Tavoni M (2017) The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob Environ Chang* 42:153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- Rochedo P (2016) Development of A global integrated energy model to evaluate the Brazilian role in climate change mitigation scenarios. Federal University of Rio de Janeiro
- Rochedo PRR, Costa IVL, Império M, Hoffmann BS, Merschmann PR d C, Oliveira CCN, Szklo A, Schaeffer R (2016) Carbon capture potential and costs in Brazil. *J Clean Prod* 131:280–295. <https://doi.org/10.1016/j.jclepro.2016.05.033>
- Rochedo PRR, Filho BS, Viola E, Schaeffer R, Szklo A, Lucena AFP, Köberle A, Davis JL, Rajão R, Rathmann R (2018) The threat of political bargaining to climate mitigation in Brazil. *Nat Clim Chang*
- Roelofsma M, van Soest HL, Harmsen M, van Vuuren DP, Bertram C, den Elzen M, Höhne N, Iacobuta G, Krey V, Kriegler E, Luderer G, Riahi K, Ueckerdt F, Després J, Drouet L, Emmerling J, Frank S, Fricko O, Gidden M, Humpenöder F, Huppmann D, Fujimori S, Fragkiadakis K, Gi K, Keramidas K, Köberle AC, Aleluia Reis L, Rochedo P, Schaeffer R, Oshiro K, Vrontisi Z, Chen W, Iyer GC, Edmonds J, Kannavou M, Jiang K, Mathur R, Safonov G, Vishwanathan SS (2020) Taking stock of national climate policies to evaluate implementation of the Paris agreement. *Nat Commun* 11:2096. <https://doi.org/10.1038/s41467-020-15414-6>
- Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K, Meinshausen M (2016) Paris Agreement climate proposals need boost to keep warming well below 2°C. *Nature* 534:631–639. <https://doi.org/10.1038/nature18307>
- Rogelj J, Shindell D, Jiang K, Ffifita S, Forster P, Ginzburg V, Handa C, Khesghi H, Kobayashi S, Kriegler E, Mundaca L, Séférian R, Vilarinho MV (2018) Mitigation pathways compatible with 1.5°C in the context of sustainable development, in: Flato, G., Fuglestedt, J., Mrabet, R., Schaeffer, R. (Eds.), *Global warming of 1.5 °C: an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. Intergovernmental Panel on Climate Change (IPCC)*
- Rose SKR, Glub AA, Sohngen B (2013) Total factor and relative agricultural productivity and deforestation. *Am J Agric Econ* 95:426–434. <https://doi.org/10.1093/ajae/aas113>
- Roy J, Tschakert P, Waisman H, Halim SA, Antwi-Agyei P, Dasgupta P, Hayward B, Kanninen M, Liverman D, Okereke C, Pinho PF, Riahi K, Rodriguez AGS (2018) Sustainable Development, Poverty Eradication and Reducing Inequalities, in: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change.*. In Press
- Schaeffer R, Köberle A, van Soest HL, Bertram C, Luderer G, Riahi K, Krey V, Vuuren DP van, Kriegler E, Fujimori S, Chen W, He C, Vrontisi Z, Vishwanathan S, Garg A, Mathur R, Shekhar S, Oshiro K, Ueckerdt F, Safonov G, Iyer G, Gi K, Potashnikov V (2020) Comparing transformation pathways across major economies. *Clim Change* this issue
- SEEG (2019) Total emissions by sector [WWW document]. Sist. Estim. Emiss. e Remoções Gases Efeito Estufa. URL [http://plataforma.seeg.eco.br/total\\_emission](http://plataforma.seeg.eco.br/total_emission) (Accessed 7.1.20)
- Simioni T, Schaeffer R (2019) Georeferenced operating-efficiency solar potential maps with local weather conditions—an application to Brazil. *Sol Energy* 184:345–355. <https://doi.org/10.1016/j.solener.2019.04.006>
- Smeets EMW, Faaij APC (2010) The impact of sustainability criteria on the costs and potentials of bioenergy production—applied for case studies in Brazil and Ukraine. *Biomass Bioenergy* 34:319–333. <https://doi.org/10.1016/J.BIOMBIOE.2009.11.003>

- Soares-filho B, Rajão R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H, Alencar A (2014) Cracking Brazil's forest code. *Science* 344:363–364
- Strassburg BBN, Latawiec AE, Barioni LG, Nobre C a, da Silva VP, Valentim JF, Vianna M, Assad ED (2014) When enough should be enough: improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Glob Environ Chang* 28:84–97. <https://doi.org/10.1016/j.gloenvcha.2014.06.001>
- Szklo A, Lucena A, Schaeffer R, Filho BSS, Davis JL, Rajão R, Haddad EA, Domingues EP, Campos A, Koberle A, Ribeiro A, Lima E, Barbosa FA, Império M, Rochedo P, Maia S, Costa WLS (2017) Modelagem integrada e impactos econômicos de opções setoriais de baixo carbono. Brasília: Ministério da Ciência, Tecnologia, Inovações e Comunicações, ONU Meio Ambiente
- Szklo A, Lucena AF, Schaeffer R, Soares Filho BS, Davis JL, Rajão R, Haddad EA, Domingues EP, Campos A, Koberle AC, Ribeiro A, Lima E, Barbosa FA, Imperio M, Rochedo PRR, Maia S, Costa WLS (2018) Modelagem integrada e impactos econômicos de opções setoriais de baixo carbono. Brasília, Brasil: Ministério da Ciência, Tecnologia, Inovações e Comunicações, ONU Meio Ambiente
- Tagomori I (2017) POTENCIAL TÉCNICO E ECONÔMICO PARA A PRODUÇÃO de FISCHER-TROPSCH DIESEL A PARTIR DE BIOMASSA (FT-BTL) ASSOCIADA À CAPTURA DE CARBONO NO BRASIL. Federal University of Rio de Janeiro
- Tagomori IS, Carvalho FM, da Silva FTF, Paulo PR, Rochedo PRR, Szklo A, Schaeffer R (2018) Designing an optimum carbon capture and transportation network by integrating ethanol distilleries with fossil-fuel processing plants in Brazil. *Int J Greenhouse Gas Control* 68:112–127. <https://doi.org/10.1016/j.ijggc.2017.10.013>
- Tagomori IS, Rochedo PRR, Szklo A (2019) Biomass and bioenergy techno-economic and georeferenced analysis of forestry residues-based Fischer-Tropsch diesel with carbon capture in Brazil. *Biomass Bioenergy* 123:134–148. <https://doi.org/10.1016/j.biombioe.2019.02.018>
- UNFCCC (2015) Paris agreement, conference of the parties on its twenty-first session. UN Framework Convention on Climate Change (UNFCCC), Paris, France. FCCC/CP/2015/L.9/Rev.1
- van den Berg NJ, van Soest HL, Hof AF, den Elzen MGJ, van Vuuren DP, Chen W, Drouet L, Emmerling J, Fujimori S, Höhne N, Koberle AC, McCollum D, Schaeffer R, Shekhar S, Vishwanathan SS, Vrontisi Z, Blok K (2019) Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Clim Chang*. <https://doi.org/10.1007/s10584-019-02368-y>
- von Stechow C, Minx JC, Riahi K, Jewell J, McCollum DL, Callaghan MW, Bertram C, Luderer G, Baiocchi G (2016) 2 °C and SDGs: united they stand, divided they fall? *Environ Res Lett* 11:34022. <https://doi.org/10.1088/1748-9326/11/3/034022>

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