

on household budgets, especially those of the poorest income groups. Using this framework, we aim to understand to what extent agricultural and biofuels expansion under NDC implementation in Brazil could contribute to environmental, social, and economic objectives. Furthermore, which set of policies could reduce, or potentially offset, adverse negative outcomes caused by these isolated policies.

2 Approach

2.1 Integrating Computable General Equilibrium (CGE) and Land Use Modelling

Land-use economic models in partial equilibrium have been extensively explored in history. Since their use covers a broad range of applications, they have been employed to measure impacts of land-use policies, implementation of new energy systems and technologies, food demand shocks or biophysical constraints on agricultural development, commodity prices, land allocation, among other, [16], [32], [48]. A positive attribute of them is that they allow considering the spatial heterogeneity of land characteristics and include various levels of detail about biophysical processes.

However, these models ignore the rest of the economy. They fail to capture economy-wide feedbacks on sectors that are directly and indirectly linked with land-use. For instance, they usually ignore crucial interactions from energy industries, commodities, labour, and capital markets. Also, they do not perform broad socio-economical assessments of land-use related issues. Conversely, one of the main facets of CGE models is their ability to connect agricultural markets and land-use choices to the rest of the economy. Their pitfall relies of the fact that they usually include only rough representations of land allocation, with the land modelled as a homogenous and perfectly mobile production factor between a limited number of agriculture sectors. The strength of one is the weakness of other.

Two lines of research aim to overcome the limitations of partial and general equilibrium approaches. The first line of research consists in directly improving CGE models with added details on crops, commodities, technology, and better land supply representation [21]. For instance, models may include bioenergy technologies as latent technologies [46] or rely on more disaggregated databases, [1], [52]. In addition, Land supply

representation can be based on more advanced land supply functions [11] or distinct agro-ecological zones (AEZ) [27] which contributes to greater representativity of the models. Advanced CGE models usually include a mix of these features, [25], [53]. The second line of research links a detailed land-use model in partial equilibrium to the economy-wide model or CGE. Here, models can be either “hard-linked” through direct integration of both models [20] or “soft-coupled”, with the land-use model linked to a full multi-sector CGE model through iterative runs, exchanging data until final convergence is reached, [47], [54]. Soft-coupling has the advantage that a higher level of detail about both land-use and economy-wide processes is kept. This is also the approach we adopt in this paper.

2.2 Integrating CGE and Land Use Modelling for Brazil

We use a soft-link to couple the IMACLIM-BR CGE with the Brazilian Land Use Model (BLUM). IMACLIM-BR is a hybrid, recursive CGE; BLUM is a partial equilibrium model dedicated to land use. Between both, data on GDP and demand for biofuels, agriculture, and livestock goods is exchanged, as is information on investments needs by each sector to support its way of production. Interactive runs are conducted until reaching convergence between the two models. In practice, a data template was used to exchange the datasets between both models. This template was filled in with each model’s outputs: the outputs of one model functioned as inputs for the other model, and the latter’s outputs then served as inputs to the first model, leading to the iterative runs.

2.3 The Brazilian Land Use Model (BLUM)

The BLUM is a dynamic, partial equilibrium, multi-regional, and multi-market economic model specifically tailored for the Brazilian agricultural sectors. It is composed by two modules, both dedicated to model the following aspects of agricultural commodities: supply-demand and land use. BLUM works with the global system of Food and Agricultural Policy Research Institute (FAPRI) [35] but considering only the Brazilian territory [15]. The model has been instrumental in the Renewable Fuel Standard 2 [5] and to substantiate the Brazilian government’s proposal for NDC at COP21, [24], [36].

Dynamic interactions are key to BLUM. They simultaneously define a vector of equilibrium prices

and quantities in the Supply-Demand module [38]. National demand is composed of domestic consumption, exports, and final stocks. Its main determinants are prices, income, population, consumption patterns. Supply at national level is defined by the sum of production in Brazil's six geographic regions, as well as initial stocks (equal to the final stocks of the previous year) and imports. Feedstock production itself is represented as the result of simple multiplication of the area harvested by productivity. For agroindustry goods, BLUM considers efficiencies and production costs on the industrial part as well as migration between technologies. BLUM's land use module allows simulating for competition between agricultural crops, pastures, and native vegetation. The results can then be further detailed using a spatial allocation proprietary model. Finally, competition elasticities simulate intraregional land competition in agricultural activities (i.e., competition between the country's six geographical regions).

Expansion elasticities in BLUM indicate a need for producers to increase the total agricultural area of a region, generating deforestation. For our analysis, we estimated the elasticities under symmetry, homogeneity, and additionality constraints [17] using geo-referenced and regional production data as a primary information source [15].

Yields we projected as functions of the past ten years, allowing for small responses to long-term profitability (reflecting additional investments in R&D) and short-term profitability (which induces higher use of agricultural inputs). Yields are also affected by climate change. Average yield reduction expected for the agricultural crop (as a percentage of yield potential) was calculated for the six geographic regions using plant growth models subjected to future climate scenario and downscaled weather data [58]. The average percentage yield reduction due to climate change was then integrated into our study's baseline scenario, described in the next section of this paper.

2.3.1 CGE model: IMACLIM-BR

IMACLIM-BR is a CGE model designed to assess medium or long-term macroeconomic and social implications of climate and energy policies in Brazil, [22], [23], [55], [57]. Built under a social accounting matrix framework, it details not only Brazilian economic flows, but also physical flows (as energy, industry, and food commodities) are fully described to embark technical information from Brazilian energy and land-use scenarios. This

is important to assure the consistency with mid to long-term energy-economy projections. IMACLIM-BR represents Brazil as an open economy but includes specific structural assumptions, helping overcome some of the shortcomings of closed economy models and improving empirical and policy relevance.

The base year of the model is 2015. IMACLIM-BR has 19 productive sectors, including energy (biomass, oil, oil derivatives, and electricity), passenger transport, agriculture, livestock, and services. We disaggregated ten income classes for our analysis, helping to explain the implications of each scenario on income distribution, consumption, and the impact on other inequalities.

Models based on static production frontiers are represented by constant elasticity of substitution production functions (CES) and endogenously calibrated based on past data. This is not the case of IMACLIM-BR. Of course, it is very difficult to accurately portray long-term production frontiers which are the consequences of different price vectors and linked to technologies that will only be available in the long-term future. The way IMACLIM-BR deals with this is by exogenously incorporating long-term production frontiers into the model. Data and information are collected from experts and dedicated sectoral models (bottom-up or engineering models) which then help describe relevant innovation potential curves and allow for data exchanges between different sectors, their production and consumption, [24], [57].

Additionally, IMACLIM-BR can model cash flows, total investments per period, fuel substitution, energy efficiency, among other components. As a result, we have a model capable to properly set up changes in the technical coefficients making robust projections of available technologies, costs and its impacts over the economy during the time horizon of the study, [28], [29], [56], [57]. A detailed description of the model can be found on [30].

2.4 Scenarios

We construct a set of five scenarios to understand the consequences of NDC and associated policy implementation until 2030 under different levels of commitment to policy implementation. Scenario 1 is the baseline or reference scenario (REF). It does not consider climate change. Table 1 shows the main hypotheses and data used for the scenario.

Table 1. Main hypotheses and data for reference scenario (REF)

	Unit	2010	2020	2030
Population	Millions	191	212	223
GDP Growth (World)	% per year	5.2	4.0	3.5
GDP Growth (Brazil)	% per year	7.5	2.5	2.5
Inflation rate (Brazil)	% per year	7.3	4.5	4.5
Exchange rate	RS/USD	1.8	4.1	5.2
Oil price	USD/Barrel	77	61	95

Sources: [3], [18], [42], [44].

The four remaining scenarios are the alternative scenarios. They consider different aspects relevant to NDC/climate change policy implementation. Scenarios 1 and 2 (CC1 and CC2) allow for an increase of pressure on land use, whereas scenarios 3 and 4 (CC3 and CC4) focus on solutions to alleviate that pressure. Table 2 describes the hypotheses that we have used to build each one of these alternative scenarios.

Table 2. Main hypotheses for alternative scenarios (CC1 to CC4)

Scenario	Description
Alternative Scenario 1 (CC1)	Identical to the reference scenario, except: + changes in agricultural yield due to climate change (mainly due to changes in temperature and precipitation patterns)
Alternative Scenario 2 (CC2)	Identical to CC1, but with intensified pressures on land use/availability of land for agricultural/biofuels production. Includes: + 12 million ha restoration + Fixed ethanol mandate (54 bi litres of ethanol, of which 2,5 are second generation) + 68 TWh of bioelectricity
Alternative Scenario 3 (CC3)	Identical to CC2, but in addition including: + recovery of 15 million ha of degraded pastures + 5 million ha of ICLFS
Alternative Scenario 4 (CC4)	Identical to CC3, but in addition including: + improvements in mobility: Implementations of a low carbon program for the transport sector as described in, [24], including measures like: energy efficiency programs for light and heavy-duty vehicles, investments in railways, waterways and subways, BRTs, etc (leading to a smaller consumption of ethanol and biodiesel). Total accumulated cost of this investment program, from 2016 to 2030, is estimated at 35 billion dollars (2015 USD). + Improvements in 2G ethanol technology.

Sources: [3], [24], [37].

Changes in agricultural yield due to, for instance, reshaping temperature and precipitation patterns, are

equally contemplated from CC1 to CC4. However, CC2 represents a more intense picture in terms of the climate change pressure on land use. The 12 million hectares of forest represent the implementation of Brazil’s Forest Code and the Brazilian NDC, with the specific objective for forest recovery of those areas according to regional requirements for law compliance, [37], [49], [50].

3 Results

3.1 Scenarios

3.1.1 Reference Scenario

Figure 1 shows the used area and levels of agricultural production until 2030 for the REF scenario. We group agricultural production into grains, meat (beef, pigs, and poultry), and biofuels (ethanol, with some part coming from sugar production, and biodiesel, produced mainly from soybean). The agricultural area includes annual crops (grains, except 2nd season and winter crops), sugarcane, commercial forest, and pastures. Production outcomes are presented in % growth, and area outcomes in absolute values.

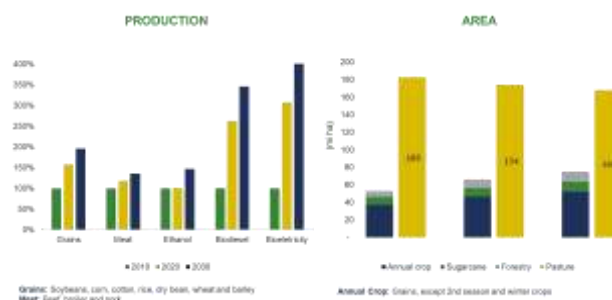


Fig. 1: Agricultural production and land use change in the reference scenario (REF).

Source: Authors

Grain production increases significantly until 2030 in the REF scenario, almost doubling in 20 years. This can be mainly explained by an increase of soybean exports, demand for meat (indirectly affecting demand for grains) and biodiesel (particularly soybean oil). The meat sector (linked to pasture demand) shows a less steeped growth compared with grains but still performs a strong expansion of 36%.

Ethanol projection is marked by two distinct periods: up to 2020 and from 2020 to 2030. At first, the sector shows only timid growth of less than one billion litre/year. This is mainly due to structural difficulties. The sector grows at a more accelerated pace from 2020 to 2030, with production reaching

40 billion litres. The production of biodiesel follows diesel demand and Brazil's biodiesel blending mandate of 10% in volumetric terms, not showing any growth potential beyond this blending mandate. From the land use perspective, annual crops expand from 37 million hectares in 2010 to 52 million hectares in 2030. The increase in terms of production is therefore 2.5 times higher than the increase of the area used in this period. The difference is explained by the expansion of second crops (which do not require additional area for production) and yields. In 2030, corn second crop accounts for almost 75% of domestic corn production, contrasting with 40% in 2010. The expansion of sugarcane area is relatively modest (24%), especially when compared with the sugarcane crush expansion (38%). The area planted with commercial forest grows from less than 7 million hectares in 2010 to over 11 million hectares by 2030. Only pasture faces area reduction compared with 2010. Pasture experiences a reduction of 15 million hectares due to the need of additional area for agricultural production. Despite a 35% increase in beef production, total pasture area is reduced by 8% between 2010 and 2030. The trend to adopt medium and high technology systems in livestock production, as observed in recent years, mainly explains this.

In REF, total land used by agriculture and livestock (production of grains, sugar cane, forest, and pastures) grows from 236 to 243 million hectares between 2010 and 2030, resulting in a total expansion of 7 million hectares. For the sake of simplicity, we assume that 7 million hectares of native vegetation would be necessary to satisfy this demand for land between 2010 and 2030.

3.1.2 Alternative Scenario

In Figure 2, the agricultural production (Figure 2.A), area (Figure 2.B), and prices (Figure 2.C) are presented in relative terms, whereas GHG emissions are presented in absolute terms (Figure 2.D).



Fig. 2: Results of reference and alternative scenarios for production, area, prices and annual GHG emissions in 2030.

Source: Authors

In annual crops markets, prices tend to increase due to inelastic demand curves for agricultural commodities while production area tends to increase with higher associated AFOLU emissions from land use (see Figure 2.C, 2.B, and 2.D). Ethanol is an exception of these trends. It is an almost perfect substitute for gasoline and thus represents higher demand elasticities. In this context, scenario CC1 would lead to a limited impact on agricultural output, except for ethanol. For the regional estimates of crop yield variations due to climate change, only two regions show yield decreases greater than 5%. Of course, significant climatic impact can still be expected at the micro-regional level, and long-run climate change is likely to affect agricultural outputs more strongly. CC2 scenario is the first of our scenarios for which we consider partial NDC implementation. Compared to REF, CC2 is marked by two major developments: strong expansion of ethanol and afforestation. Ethanol production increases over 35% (Figure 2.A) which requires about 15% more land (Figure 2.B) as part of sugarcane is also used for sugar production. Afforestation reduces the total area available to agriculture, with particular impact on pastureland and annual crops (Figure 2.B). The combination of climate change, higher ethanol production, and large-scale afforestation thus result in a stress in terms of commodity markets, with average prices growing between 8% (grains) and 15% (sugarcane) – see Figure 2.C. This leads to a significant reduction of GHG emissions in the AFOLU sector, dropping it to about 125 million tons of CO_{2eq} per year in 2030. We should note that substitution of gasoline by ethanol is not accounted in this figure meaning that overall emissions reductions in this scenario and CC3 and CC4 would likely be even higher.

CC3 scenario represents the additional recovery of 15 million ha of degraded pastures and implementation of 5 million ha of ICLFS. Both measures enhance the productivity in the livestock sector (which is currently the sector using the largest parcel of land). Higher efficiency in the livestock sector releases pressure in the land market, reducing prices (mostly meat, but also grains and sugarcane), and allowing not only higher consumption but also an increase in terms of agricultural production. The GHG emissions in this scenario also decrease to 344 million tons of CO_{2eq} by 2030 (195 lower than REF).

In CC4 we consider additional improvements in the transport sector. In addition, more ethanol is produced due to the use of sugarcane bagasse for ethanol production, including for co-generation. Adding second generation biofuels drives gains in terms of productivity in bioenergy production. All these assumptions result into a lesser demand for agricultural feedstock which consequently reduces pressures on land use. This, in turn, leads to decreases in grains and ethanol prices. Counterintuitively, meat prices increase. As biodiesel reduces its demand for soybean oil, its production becomes less attractive, affecting the feed availability. The raise of feed prices indirectly increases the prices of proteins since feed plays a relevant role in its cost structure.

3.2 Macroeconomic and Social Results

Table 3 shows the macroeconomic outcomes of the climate change scenario (CC1) and the implementation of land use related mitigation measures (CC2 to CC4). Overall, macroeconomic outcomes are rather limited until 2030. For instance, all of the five scenarios present GDP values for 2030 at around 2.3 Billion 2015 USD. Annual GDP growth rates vary only between 2.09% (CC1 scenario) to 2.11% (REF and CC4 scenarios). As a result, total GDP per capita is also similar across all five scenarios (US\$ 10.286 per capita to US\$ 10.311 per capita).

Table 3. Macroeconomic results

	Unit	2015	REF 2030	CC1 2030	CC2 2030	CC3 2030	CC4 2030
GDP	Billion 2015 USD	1,681	2,299	2,294	2,294	2,296	2,298
GDP growth per year	% per year	-	2.11	2.09	2.10	2.10	2.11
GDP/capita	Thousand 2015 USD/capita	7.93	10.31	10.29	10.29	10.30	10.31
Investment rate	% of GDP	16.4	19.2	18.4	18.5	18.8	19.0
Trade balance	% of GDP	4.3	3.8	3.4	2.9	3.3	3.6
Price index	% increase in relation to REF	-	-	1.8	3.1	2.5	2.3
Number of full-time jobs	Million jobs	99.8	117.8	117.2	117.3	117.5	117.7
Unemployment rate	%	8.5	7.5	7.9	7.9	7.7	7.6

Source: Authors

For 2030, all alternative scenarios have a higher price index compared to REF, with the smallest and highest values being respectively represented by CC1 and CC2. Price indexes are directly linked with the land use results. As climate change induces a slight increase of agriculture prices in the CC1 scenario, it spreads within the rest of the economy, which culminates into general prices increase of 1.8%. The NDC policies also add pressure on land in the CC2 scenario, leading to an additional increase of agriculture prices and thus the general price index of by 3.1%. As investments in the recovery of degraded pastures and on ICLFS reduce pressure on land demand, CC3 and CC4 scenarios have a lower price index than CC2 and close to the price index level of CC1.

The slight variations found in trade balance follow the price index. The smallest trade balance variations occur in CC2, where the price index is at its lowest and Brazil becomes less competitive compared to the rest of the world. Overall, climate change impacts on prices compare to those impacts caused by the implementation of the expansive mitigation policies implemented under the Brazilian NDC scenarios (CC2 to CC4).

As we go from scenario CC1 to scenario CC4, a fuller NDC implementation in fact holds macroeconomic gains for the Brazilian economy. Although those effects would still be rather small, they almost fully offset the losses caused by climate change. Even in scenario CC4, where we have simulated an extensive low carbon program for the transport sector, accumulated investments in mitigation for this sector in the period from 2016 to 2030 (35 billion 2015 USD) are only a small fraction of how much was accumulated in terms of GDP (0.1%) or what was accumulated from the perspective of investments in the whole economy in the same period (0.5%).

Figure 3.A presents socioeconomic outcomes from REF on household expenses for each one of the six IMACLIM-BR household classes. While class 1 represents the 10% poorest families roughly corresponding to the population under the poverty line with less than US\$5.5 per day, 2-5 classes stand for the intermediate category, divided into 20% groups. Class 6 represents the 10% of richest families. We notice that the average food expense share across classes in 2030 (around 13%) is rather low and similar to today's France (12% in 2018²), even bearing a three times lower GDP per capita. This means that reference food prices are lower in Brazil compared to international benchmarks. However, food budget shares sharply differ between classes by 2030: the poorest households (class 1) use 17% of their disposable income to buy food, while the richest households (class 6) use only 5,3% of their disposable income for the same purposes (with a greater share dedicated to "other expenses", which includes going to restaurants). We can expect that an increase of food prices will lead to increased food insecurity as food access becomes more and more difficult, especially for poorer households.³⁴

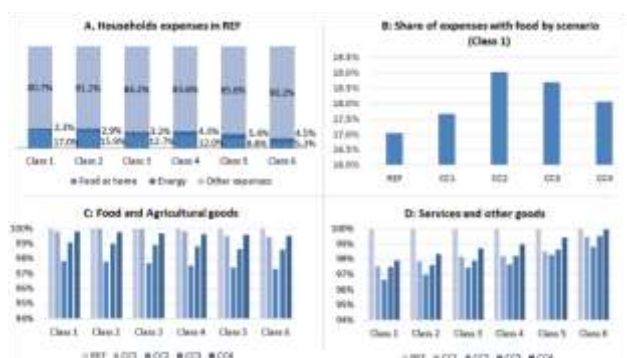


Fig. 3: Household's expenses in 2030
 Source: Authors

Figure 3.C shows the variations of the physical consumption of food across households' classes and scenarios. Higher food prices from CC1 to CC4 compared to REF lead to lower relative food consumption, which decreases less for the lower than higher classes. The lower price elasticity of

poorer households' food consumption is expected to intensify the regressive impact of food price increase.

As food prices increase, so does the amount people would have to spend on buying food, constraining food consumption. Figure 3.B shows the resulting food expense share of household class 1 across all five scenarios. Class 1 food expense share reaches its peak under the partial implementation of the NDC case (CC2), resulting in a 12% increase compared to REF and a 2-point increase of budget share. These are directly linked to our agriculture and food price increase projections for that scenario. Taking a different course, CC3 and particularly CC4, alleviate the pressure on land use and food prices, substantially reducing the tension on household budgets. Overall, the food expense shares of class 1 in our scenarios stay below 20% which is still far from the food insecurity thresholds usually considered by previous studies⁵.

Figure 3.D shows the resulting impacts on household consumption of services and other goods. The results reflect the purchasing power of households outside food and energy expenses. We can first notice that average consumption impacts of climate change and NDC policies on households are significantly higher than GDP impacts. Also, in CC2 consumption 2% lower in average than REF (3.3% lower for class 1). However, the additional policies to alleviate pressure on land and decreased biofuel demand in CC4 offset almost half of the average consumption losses in CC1, increasing the average well-being of families in a climate change context. Notwithstanding, as expected, climate change and NDC policies have a regressive impact on households' consumption. The poorer classes are relatively more impacted than the richer classes. Poorer households significantly reduce their expenses on services and other goods in order to secure their disposable income for buying food. This is even more evident in scenarios where food prices are more impacted, such as CC2. On the other hand, richer households need to do little to change their consumption patterns. From the CC3 and CC4 policies perspective, although providing an average consumption dividend compared to CC2 (also, compared to CC1 with CC4), they do not reduce the regressivity of the impacts. Furthermore, the consumption surplus of CC4 compared to CC1 is

²These data can be found in OECD, 2022.

³ The literature on poverty and food security, [40], [45] consent that poorer households consume food near minimum security limits, and thus have less possibility of further reducing it than well-off households.

⁴ Observation: as class 1 (poor households) do not have private cars or expensive home appliances, they keep their energy consumption per capita lower (including biofuels) than richer classes. Because of this no changes in energy consumption are observed.

⁵ In some studies, households are considered as food insecure if their food expense share is higher than 50% [51].

moved even more to richer households than the poorer. Additional policies are needed to correct the distributive implications of NDC policies.

4 Discussion and Conclusions

Our paper shows how the agricultural sector is affected by AFOLU-related NDC implementation and its consequences at the macroeconomic and social level in Brazil. When degraded lands are recovered, ICLFS are implemented, and strong 2nd generation biofuels growth is put in place, these negative effects can be mostly offset. This is particularly the case in more sustainably oriented scenarios CC3 and CC4 which also present several important co-benefits in well-being, food security and reducing the pressure over Amazon deforestation. There are also considerable changes in AFOLU and energy related GHG emissions, with both CC3 and CC4 scenarios presenting considerable emissions reductions compared to REF. Our analysis thus shows that NDC implementation in Brazil is considerably preferable to a business-as-usual development pathway, particularly once climate change impacts are taken into consideration. While economic sectors are quite differently affected (e.g., lower meat and grains production against substantially higher ethanol production in all NDC scenarios except CC4), we find only a limited macroeconomic impact for all scenarios which consider climate change (CC1-CC4), despite heavy investments in conservation, land restoration, and biofuels deployment (both soybean and ethanol production). This limited impact may be due to the following: (1) we have not analysed any climate change scenario considered extreme (which makes sense given our horizon is 2030); (2) and related) our simulations period is short (from up to 2030); (3) we have considered a limited weight in terms of the investments in public transport and energy efficiency in relation to the total investments of the economy while (4) there is a positive “corrective nature” of these investments in promoting efficiency across the Brazilian economy.

We also do only find a limited impact for all climate change scenarios for total family income by class which varies little across the scenarios.

In fact, across all scenarios, when considering climate change impact, the partial implementation of the NDC actions increases the pressure on land and prices of goods that require land as input (very clear in the CC2 scenario). However, as further steps into full implementation of NDC are taken,

land pressure is reduced, decreasing also GHG emissions. In the same way, less pressure in land use leads to a lower share of income locked in food consumption.

On the other hand, our analysis shows that the way families spend their income across scenarios reveals important impacts. As poorer classes already consume food near their lower subsistence limit, they have less room to further reduce their consumption in case of food prices increase. As a result, poorer families end up spending a larger share of their income on food while reducing their physical consumption. With a higher share of income compromised for food, to balance back their budget, poorer families need to reduce the consumption of services and other goods. This result brings to light the loss of well-being in most critical scenarios (especially CC2). Richer families suffer much less the impacts of food price increases as only a minor part of their income is allocated to food. Similarly, the share of income committed to services and other goods is much less affected in higher classes. It confirms that poorer household classes would suffer more from climate change impacts and higher food prices.

Scenarios CC3 and particularly CC4 present slightly different development trajectories for Brazil that are worth to consider. They do not show negative impacts on GDP growth and other macroeconomic indicators and, in fact, perform better from a socioeconomic and environmental perspective, with extensive investment programs aiming to encourage public transportation and promote energy efficiency gains for light and heavy vehicles which would lessen the need for fossil fuels and biofuels. These scenarios would also reduce pressure on land use, Amazon deforestation, food prices, and GHG emissions. This is the case of scenarios CC3 and, particularly, CC4. Poorer families would be benefited from such “new” development trajectories as their food consumption and well-being would be closer to what was observed in the hypothetical REF scenario which does not take climate change into the analysis (and is thus truly hypothetical, as a no climate change scenario is no longer a reality). Not to mention that these scenarios would be preferable given their important leverage for the realization of synergies between socioeconomic development, conservation, and climate protection. These scenarios provide clear links not only to the COP/UNFCCC process but also green or low carbon growth concepts or the 2030 Agenda for Sustainable Development, [12], [13]. Our results

indicate that little would be lost by turning the Brazilian economy towards these alternative development trajectories which would likely contribute to these targets.

Our analysis requires two words of caution: first, our scenarios rely on a conservative interpretation of the future which does not reflect a true potential of either economic growth rates or climate change impacts. Putting more pressure on our simulations by using higher economic growth rates, severer climate change impacts, also, stricter land use policies could amplify existing trade-offs and make decisions on policy implementations such as NDC more complicated. Second, the current policy situation in Brazil regarding implementations of environmental protection (e.g., zeroing in on illegal deforestation) and agricultural development has changed considerably in the past years.

To conclude, our modelling exercise shows that green or low carbon growth scenarios bring important social and environmental benefits. With the new federal administration recently elected, and its compromise to reduce Amazon deforestation and GHG emissions, the results found on this research shows a highly desirable pathway for Brazil.

References:

- [1] Birur, Dileep; Hertel, Thomas; Tyner, Wally; Impact of biofuel production on world agricultural markets: a computable general equilibrium analysis, *GTAP Working Paper No. 5*, 2007. Retrieved from https://www.researchgate.net/publication/5081758_Impact_of_Biofuel_Production_on_World_Agricultural_Markets_A_Computable_Genera
- [2] Brasil (Ed.), *Intended Nationally Determined Contribution*. Brasília: República Federativa do Brasil, 2015.
- [3] Brasil, *Relatório de Inflação*. Banco Central do Brasil. Brasília, Brasil, 2016.
- [4] CEPEA, *Em 2017, PIB cresce, mas agronegócio tem menos ocupados*, 2018. Retrieved from <https://www.cepea.esalq.usp.br/br/releases/mercado-de-trabalho-cepea-em-2017-pib-cresce-mas-agronegocio-tem-menos-ocupados.aspx>
- [5] EPA, *Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program - Final rule: Federal Register / Vol. 75, No. 58 / Friday, 26*, United States Environmental Protection Agency (EPA), 2010. Retrieved from <https://www.gpo.gov/fdsys/pkg/FR-2010-03-26/pdf/2010-3851.pdf>
- [6] EPE, *O Compromisso do Brasil no Combate às Mudanças Climáticas: Produção e Uso de Energia*. Rio de Janeiro: Energia de Pesquisa Energética (EPE), 2016.
- [7] Fearnside, P., Business as usual: a resurgence of deforestation in the Brazilian Amazon. *Yale Environ*, 360, 2017.
- [8] Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., ... White, L. L. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014.
- [9] Fragkos, P., Fragkiadakis, K., Paroussos, L., Pierfederici, R., Vishwanathan, S. S., Köberle, A. C., ... Oshiro, K., Coupling national and global models to explore policy impacts of NDCs. *Energy Policy*, 118, 462–473, 2018. <https://doi.org/10.1016/j.enpol.2018.04.002>
- [10] Frank, S., Havlík, P., Soussana, J.-F., Levesque, A., Valin, H., Wollenberg, E., ... Obersteiner, M., Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, 12(10), 105004, 2017. <https://doi.org/10.1088/1748-9326/aa8c83>
- [11] Fujimori, S., Hasegawa, T., Masui, T., & Takahashi, K., Land use representation in a global CGE model for long-term simulation: CET vs. logit functions. *Food Security*, 6(5), 685–699, 2014. <https://doi.org/10.1007/s12571-014-0375-z>
- [12] Future Earth (Ed.), *Research and Engagement Plan for the Water-Energy-Food Knowledge-Action Network*. Report of the Development Team, 2018.
- [13] Griggs, D. J., Nilsson, M., Stevance, A., McCollum, D., & others, *A guide to SDG interactions: from science to implementation*: International Council for Science, Paris, 2017.
- [14] Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., ... Fargione, J., Natural climate solutions, *Proceedings of the National Academy of Sciences of the United States of America*, 114(44), 11645–11650, 2017. <https://doi.org/10.1073/pnas.1710465114>
- [15] Harfuch, L., Bachion, L. C., Moreira, M. M. R., Nassar, A. M., & Carriquiry, M., *Empirical*

Findings from Agricultural Expansion and Land Use Change in Brazil, In *Handbook of Bioenergy Economics and Policy: Volume II* (pp. 273–302). Springer, 2017.

- [16] Havlík, Petr; Valin, Hugo; Gusti, Mykola; Schmid, Erwin; Leclère, David; Forsell, Nicklas; Herrero, Mario; Khabarov, Nikolay; Mosnier, Aline; Cantele, Matthew; Obersteiner, Michael; *Climate Change Impacts and Mitigation in the Developing World: An Integrated Assessment of the Agriculture and Forestry Sectors*, *World Bank Policy Research Working Paper*, No. 7477, 2015. Available at SSRN: <https://ssrn.com/abstract=2688375>
- [17] Holt, M. T., A linear approximate acreage allocation model. *Journal of Agricultural and Resource Economics*, 383–397, 1999.
- [18] IBGE, Projeção da população do Brasil e das Unidades da Federação, 2014. Disponível em <http://www.ibge.gov.br/apps/populacao/projecao/>.
- [19] INPE/Terrabrasilis, Taxas de desmatamento Amazônia Legal - estados. 2022 http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/rates
- [20] Klein, D., Luderer, G., Kriegler, E., Strefler, J., Bauer, N., Leimbach, M., ... Edenhofer, O., The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE. *Climatic Change*, 123(3-4), 705–718, 2014. <https://doi.org/10.1007/s10584-013-0940-z>
- [21] Kretschmer, B.; Peterson, S.; Integrating bioenergy into computable general equilibrium models — A survey. *Energy Economics*, 32(3), 673–686, 2010. <https://doi.org/10.1016/j.eneco.2009.09.011>
- [22] La Rovere, E. L.; Grottera, C.; Wills, W.; Overcoming the financial barrier to a low emission development strategy in Brazil. *International Economics*, 2018a. <https://doi.org/10.1016/j.inteco.2017.12.004>
- [23] La Rovere, E. L.; Wills, W.; Grottera, C.; Dubeux, C.B.S.; Gesteira, C.; Economic and social implications of low-emissions development pathways in Brazil. *Carbon Management*, 2018b. <https://doi.org/10.1080/17583004.2018.1507413>
- [24] La Rovere, E. L.; Wills, W.; Pereira, A.; Dubeux, C. B.; Cunha, S. H.F.; Oliveira, B. C.P.; ... others, *Implicações Econômicas e Sociais de Cenários de Mitigação de Gases de Efeito Estufa no Brasil até 2030 - Sumário Técnico*. Rio de Janeiro: Forum Brasileiro de Mudanças Climáticas (FBMC), 2016.
- [25] Laborde, D., & Valin, H., Modelling land-use changes in a global CGE: assessing the EU biofuel mandate with the Mirage-BioF model. *Climate Change Economics*, 03(03), 1250017, 2012. <https://doi.org/10.1142/S2010007812500170>
- [26] Lapola, D. M., Martinelli, L. A., Peres, C. A., Ometto, J. P. H. B., Ferreira, M. E., Nobre, C. A., ... Vieira, I. C. G., Pervasive transition of the Brazilian land-use system. *Nature Climate Change*, 4(1), 27–35, 2014. <https://doi.org/10.1038/nclimate2056>
- [27] Lee, David S., et al. “Aviation and global climate change in the 21st century.” *Atmospheric environment* 43.22-23: 3520-3537, 2009.
- [28] Lefèvre, J., *Hybridization challenges in energy-economy integrated models and representation of the low carbon transition: An application to the Brazilian case*. Université Paris Saclay, 2016.
- [29] Lefèvre, J., Wills, W., Hourcade, J.-C., Combining low-carbon economic development and oil exploration in Brazil? An energy- economy assessment. *Climate Policy*, 1–10, 2018.
- [30] Le Treut, Gaëlle. Description of the IMACLIM-Country model: A country-scale computable general equilibrium model to assess macroeconomic impacts of climate policies, 2020. <https://hal.archives-ouvertes.fr/hal-02949396/document>
- [31] Le Treut, Gaëlle; Combet, Emmanuel; Lefèvre, Julien; Teixeira, Antoine; Baudin, Alexis. IMACLIM-Country platform : a country-scale computable general equilibrium model, 2019 https://zenodo.org/record/3403961#.YtmeC1h0_V
- [32] Lotze- Campen, Hermann, et al. Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agricultural Economics* 39.3: 325-338, 2008.
- [33] MDIC, Balança comercial: Janeiro-dezembro 2016, 2017a. Retrieved from <http://www.mdic.gov.br/index.php/comercio-exterior/estatisticas-de-comercio-exterior/balanca-comercial-brasileira-acumulado-do-ano?layout=edit&id=2205>
- [34] MDIC, *Estimativa anuais de emissões de gases de efeito estufa no Brasil* (4th ed.). Brasília: Ministério da Indústria, Comércio Exterior e Serviços, 2017b. Retrieved from

http://sirene.mcti.gov.br/documents/1686653/1706227/4ed_ESTIMATIVAS_ANUAIS_WEB.pdf/a4376a93-c80e-4d9f-9ad2-1033649f9f93

- [35] Meyers, W. H., Westhoff, P., Fabiosa, J. F., & Hayes, D. J., The FAPRI Global Modelling System and Outlook Process. *Journal of International Agricultural Trade and Development*, 6(1), 1–20, 2010.
- [36] MMA, *Fundamentos para a elaboração da Pretendida Contribuição Nacionalmente Determinada (iNDC) do Brasil no contexto do Acordo de Paris sob a UNFCCC*. Brasília: Ministério do Meio Ambiente, 2016. Retrieved from http://www.mma.gov.br/images/arquivos/clima/convencao/indc/Bases_elaboracao_iNDC.pdf
- [37] MMA, & BID (Eds.), *Documento-Base para Subsidiar os Diálogos Estruturados sobre a Elaboração de uma Estratégia de Implementação e Financiamento da Contribuição Nacionalmente Determinada do Brasil ao Acordo de Paris*. Brasília, 2017.
- [38] Moreira, M. M. R., *Estratégias para expansão do setor sucroenergético e suas contribuições para a NDC brasileira (D.Sc.)*. Universidade Estadual de Campinas, Campinas, 2016. Retrieved from <http://repositorio.unicamp.br/handle/REPOSIP/330246?mode=full>
- [39] Obermaier, M., & Lemos, M. C., *Análise sobre projeções climáticas e seus impactos na segurança alimentar e nutricional*. Salvador: OXFAM/MMA, 2014.
- [40] Obermaier, M., Martins, R. d'A., Antoniazzi, L. B., Lemos, M. C., & Herrera, S., *Contextualização da relação entre Segurança Alimentar e Nutricional (SAN) e adaptação às mudanças climáticas: complexidade do tema e abordagens conceituais*. Salvador, 2014.
- [41] Obermaier, M., Wills, Wills, King, Carey W., Moreira, M. M., Rodriguez, R. d.G., Kimura, W., ... Bachion, L. C. Consequências da expansão de biocombustíveis no Brasil sobre uso da terra, água e a economia até 2030 sob mudanças climáticas, 2017. Retrieved from <https://www.linkedin.com/pulse/publica%C3%A7%C3%A3o-consequ%C3%Aancias-da-expans%C3%A3o-de-brasil-sobre-uso-obermaier/>
- [42] OECD, *OECD Economic Outlook, Volume 2016 Issue 1*, OECD Publishing, Paris, 2016. https://doi.org/10.1787/eco_outlook-v2016-1-en.
- [43] Olsson, L., Opondo, M., Tschakert, P., Agrawal, A., Eriksen, S. H., Ma, S., ... Zakieldean, S. A., Livelihoods and poverty. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, ... L. L. White (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (pp. 793–832). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014.
- [44] PWC, *The World in 2050. Will the shift in global economic power continue?* PWC-UK, 2015 Available at: <http://www.pwc.com/gx/en/issues/the-economy/assets/world-in-2050-february-2015.pdf>
- [45] Porter, J. R., Xie, L., Challinor, A. J., Cochrane, K., Howden, S. M., Iqbal, M. M.,... Travasso, M. I., Food security and food production systems. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir,... L. L. White (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (pp. 485–533). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014.
- [46] Reilly, John; Paltsev, Sergey; Biomass energy and competition for land, *Economic analysis of land use in global climate change policy*. Routledge, 202-225, 2009.
- [47] Ronneberger, K., Berrittella, M., Bosello, F., Tol, R. S. J., KLUM@GTAP: Introducing Biophysical Aspects of Land-Use Decisions into a Computable General Equilibrium Model a Coupling Experiment. *Environmental Modeling & Assessment*, 14(2), 149–168, 2009. <https://doi.org/10.1007/s10666-008-9177-z>
- [48] Sands, Ronald D.; Marian Leimbach; Modeling agriculture and land use in an integrated assessment framework, *Climatic Change* 56.1: 185-210, 2003.
- [49] Soares-Filho, B., Rajão, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., ... Alencar, A., Cracking Brazil's forest code. *Science*, 344(6182), 363–364, 2014.
- [50] Sparovek, G., Barretto, Alberto Giaroli de Oliveira Pereira, Matsumoto, M., & Berndes, G., Effects of governance on availability of land for agriculture and conservation in Brazil.

Environmental Science & Technology, 49(17), 10285–10293, 2015.

- [51] Smith, Lisa C.; Subandoro, Ali; *Measuring food security using household expenditure surveys*. Vol. 3. Intl Food Policy Res Inst, 2007.
- [52] Taheripour, F.; Birur, D.; Hertel, TW.; Tyner, WE.; *Introducing Liquid Biofuels into the GTAP Data Base*. Center for Global Trade Analysis, Purdue University. Global Trade Analysis Project (GTAP), GTAP Research Memorandum No. 11 No. BM, 2007 <https://www.gtap.agecon.purdue.edu/resources/download/3939.pdf>
- [53] Timilsina, G. R., Mevel, S., *Biofuels and climate change mitigation: a CGE analysis incorporating land-use change*: The World Bank, 2011.
- [54] Verstegen, J. A., van der Hilst, F., Woltjer, G., Karssenber, D., Jong, S. M. de, Faaij, A. P. C., What can and can't we say about indirect land-use change in Brazil using an integrated economic - land-use change model? *GCB Bioenergy*, 8(3), 561–578, 2016. <https://doi.org/10.1111/gcbb.12270>
- [55] Winkler, H., Delgado, R., Palma-Behnke, R., Pereira, A., Baos, T.V., Wills, W., Salazar, A., Information for a developmental approach to mitigation: linking sectoral and economy-wide models for Brazil, Chile, Colombia, Peru and South Africa. *Climate and Development*, 2016. <https://doi.org/10.1080/17565529.2016.1174660>
- [56] Wills, W., *Modelagem dos Efeitos de Longo Prazo de Políticas de Mitigação de Emissões de Gases de Efeito Estufa na Economia do Brasil*. Tese de D.Sc. Rio de Janeiro, 2013.
- [57] Wills, W., La Rovere, E.L., Grottera, C., Napolini, G.F., Le Treut, G., Ghersi, F., Lefèvre, J., Dubeux, C.B.S., Economic and social effectiveness of carbon pricing schemes to meet Brazilian NDC targets, *Climate Policy*, v.22, p.48-63, 2022.
- [58] Xavier, A. C., King, C. W., Scanlon, B. R., Daily gridded meteorological variables in Brazil (1980- 2013). *International Journal of Climatology*, 36(6), 2644–2659, 2016.
- [59] Radoslav Mavrevski, "Modelling in Food Technology", *WSEAS Transactions on Biology and Biomedicine*, vol. 16, pp. 69-74, 2019

Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

- William Wills: experiment design, CGE modeling,
- CGE and land-use link, policy analysis, and writing.
- Marcelo Moreira: land-use modeling.
- Martin Obermaier: policy analysis and writing.
- Julien Lefèvre: CGE modeling.
- Romulo Ely: Input-Output database hybridization, CGE and land-use link, and writing.

Sources of funding for research presented in a scientific article or scientific article itself

Not applied.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)

This article is published under the terms of the Creative Commons Attribution License 4.0

https://creativecommons.org/licenses/by/4.0/deed.en_US