SUPPLEMENTARY MATERIAL – MODELING TOOLS

Macroeconomic modelling

The macroeconomic scenarios used in the study establish likely limits for the trajectory of the Brazilian economy under some hypotheses. A Dynamic Stochastic General Equilibrium (DSGE) model is used, together with a Computable General Equilibrium (CGE). While the DSGE model provides the boundary conditions for macroeconomic aggregates, the CGE model generates detailed and consistent sectoral information (AZZONI et al, 2011).

The DSGE model considers interactions among five different economic agents: households, firms, the financial sector, government, and the rest of the world (KANCZUK, 2001 and 2004). These agents interact in an economic environment subject to monetary, risk, and productivity shocks. The critical element in the construction of such models is the definition of hypotheses relating to these three types of shocks. Given the long-term concern of this study, the first two are not as important, since they are usually short-lived. The results were therefore derived from a sole supposition of global inflation and nominal interest rate trajectories, taken from a world scenario. Trends in productivity, on the other hand, are essential for the determination of economic growth and investment rates. Therefore, they were considered more carefully, involving scenarios for the world economy, as well as scenarios for the internal fiscal policy and institutional framework. A production function was estimated involving capital stock and the number of hours worked; the part of production not explained by those two primary factors was considered as the effect of productivity. Prospective modeling of the trends in this residual effect was considered in detail to build the hypotheses for the baseline macroeconomic scenario. It focused on the modeling of the evolution of human capital (measured by the evolution of schooling), distortions to capital accumulation related to economic policies and institutions (measured by the relative price of investment goods), and a net productivity convergence of Brazil towards the benchmark economy, the US (measured by a convergence coefficient).

The macroeconomic scenario was the benchmarks for the construction of sectoral scenarios in the context of a Computable General Equilibrium model (HADDAD; DOMINGUES, 2001), which splits economic activity into 56 sectors and 110 commodities, including 11 different energy inputs.

In terms of energy, the EFES framework incorporated new trends in energy intensity by sector in order to adjust all sectoral projections based on information from MESSAGE. The most probable hypotheses about structural changes in the energetic matrix up to 2050 were incorporated in a semi-iterative approach.

The new energy intensities and changing energy utilization in different sectors change the results of the reference (or baseline) scenario. Changes in energy intensity and energy use were, in part, related to the expected changes in energy utilization embedded in the energy model used. Therefore, we dealt with a changing scenario considering some adaptation to climate change effects into the rates of return of each energy type (in each sector). Introducing such changes into the CGE model produced changes in the sectoral composition of production, as well as in the macroeconomic aggregates.

The EFES model has an environmental module inspired by the MMRF-Green model (ADAMS; PARMENTER, 2013). Emissions in the model are associated with sectors, such as agricultural emissions (whose cause lies in the enteric fermentation of ruminants, rice cultivation, and use of fertilizers - an important source of Brazilian emissions) or industrial processes (e.g., cement manufacture). The model calculated the carbon price, or cost of emission reductions endogenously, by imposed GHG emissions targets. Alternatively, more conventionally, the effects of imposing a carbon price in the economy. It represents the usual theoretical correlation between Pigouvian taxes and carbon prices required to achieve a pollution reduction target.

The environmental module was responsible for the transformation of carbon prices, or carbon taxes, in *ad-valorem* tax rates, feeding the core model. From the results of certain variables (changes on fuel use by sectors, 'sectors' activity, and household consumption), the environmental module calculated changes in emissions.

The government revenue from the imposition of a carbon tax was calculated as described by ADAMS and PARMENTER (2013).

In the EFES framework, there are no endogenous technological innovations to the case of fossil fuels or productive activities (less emission-intensive technologies) that allow, for example, the burning of coal to release less CO_2 per ton used in response to a carbon pricing. Probably, many of these abatement technologies or alternative production methods would become cost-effective under carbon pricing. However, appropriate values of the parameters of the abatement response functions need to be firmly established, and in the Brazilian case, there is still much uncertainty. In order to overcome this, such mechanisms were incorporated in the integration procedure with the MESSAGE model.

Energy system modelling

The GHG emissions scenarios for energy system were performed using the MESSAGE (Model for Energy Supply Strategy Alternatives and Their General Environmental Impacts), an optimization software in linear programming for energy systems developed by IIASA (International Institute for Applied System Analysis) (GRITSEVSKYI and NAKICENOV, 2000). However, the model was reconfigured entirely to ensure a better detailing of the regional breakdown as well as endogenous energy efficiency and GHG mitigation options in the end-use sectors.

The model adopts an optimization under a minimum overall cost perspective; then, it provides results that reflect the optimal conformation of an energy system in a perfect competition, which does not occur in reality. For instance, it considers perfect information, no entry and exit barriers, no transaction costs, and a homogeneous opportunity cost of capital. Thus, it was necessary to create and calibrate constraints into the model. These constraints were imposed on production and capacity expansion and made the model resemble market imperfections. This approach added to the results more reality and reliability, especially in the short term. Also, the modeling approach allowed the inclusion of environmental constraints, such as GHG emissions, which is of fundamental importance to this research.

The total cost of the system included the investment costs, operating costs, and additional costs, such as "penalties" for specific alternatives, such as environmental and social costs. The total value was calculated by discounting all the costs that occur at later points on a per year basis for the case study, and the sum of the discounted total costs was used to find the optimal solution. This approach allowed us to perform a realistic assessment of the long-term role of energy supply options in competitive conditions, as described early by LUCENA et al. (2010).

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

In sum, MESSAGE was applied to estimate the least-cost expansion strategy for the Brazilian energy supply system to meet a particular exogenous demand, under specified constraints, namely energy resource availability, industrial installation capacity of each technology, investment costs, and political, social, and environmental constraints. To this end, the model minimized the total cost of the entire energy system, considering different primary fossil and renewable energy sources and the interaction of conversion technologies to produce the required energy services to end-use sectors – industrial, energy, transport, residential, agricultural, and waste management.

AFOLU modelling

The GHG emissions scenarios for the AFOLU sector were performed using the OTIMIZAGRO (SOARES FILHO et al., 2013; SOARES FILHO et al., 2016), a nationwide, spatially-explicit model that simulates land use, land use change, forestry, deforestation, regrowth, and associated carbon emissions under various scenarios of agricultural land demand and deforestation policies for Brazil. The current land use map for Brazil (Figure 4), as of 2010, is based on a composite of forest remnants from PRODES, SOS Mata Atlântica, PROBIO, and TerraClass (HANSEN et al., 2013). The urban areas consisted of census tracts classified by the Brazilian Institute of Geography and Statistics (IBGE). Initial cropland areas were spatially allocated using soy and sugarcane maps and municipal agricultural data plus maps of crop aptitude and profitability. Crop climatic aptitude maps were developed by applying the weights of evidence method having as input municipal cropland data, and maps of mean annual temperature and hydrological balance.

In order to simulate land-use changes between 2010-2050, the model framework, developed on the Dinamica EGO platform, is structured in four spatial levels: (i) Brazil's biomes, (ii) IBGE micro-regions, (iii) Brazilian municipalities, (iv) and raster grid of 500x500 meter spatial resolution. This high resolution is necessary since the Brazilian Forest establish conservation requirements at the property level and due to the high level of heterogeneity of land uses within the same regions. The starting point of

OTIMIZAGRO is the simulation of the conservation requirements established at the property level by the Brazilian Forest Code of 2012. In particular, the model defines at property level the area of permanent preservation (APP) that varies according to the length of adjacent rivers and topography, and the size of the Legal Reserve, an area of conserved native vegetation that varies between 20 and 80% of the property size depending on the biome. Following this first step, the model calculated the area that can be legally deforested (i.e., forest surplus) and those that need to be restored or compensated (i.e., forest debt). In this way, the model simulated the land-use change under a scenario of full implementation and enforcement of the Brazilian Forest Code (SOARES-FILHO; RAJÃO et al., 2016). The model also simulated the effect of the forest quotas (CRAs) market defined in the Brazilian Forest Code. With this purpose, the total forest surplus areas by state and biome were added up with the preserved legal reserves of small properties that under the Forest Code can also issue CRAs in order to estimate the potential offer of forest quotas. Likewise, the areas with forest debt and high opportunity costs were also identified in order to estimate the potential demand for compensation. The model then calculated the supply and demand curves for the quotas, based on volumes (ha) and wiliness to pay and accept the quotas (in US$) for each municipality and biome. These curves were then aggregated at the state and biome levels to calculate the prices of the quotas, via a partial equilibrium model, as described by (SOARES-FILHO; RAJÃO et al., 2016).

The second step involved the simulation of changes from native vegetation to other land-uses respecting the restriction of the Brazilian Forest Code (Except in the Amazon biome, where the target to reduce 80% in deforestation still allows for illegal deforestation to take place towards the end of the period). As the total area deforested is variable calculated on the assumption of the full implementation of the deforestation reduction policy scenarios, it was decided to consider deforestation exogenously in order to take into account that in the frontier clearings take place as part of land grabbing and speculation processes decoupled from the expansion of agricultural production, as described by MACEDO et al., (2012). In order to establish the specific areas that are likely to be deforested under these policy scenarios, OTIMIZAGRO implemented a cellular automata model that calculates a probability map depicting the aggregate influence of spatial factors on the location of deforestation. The spatial factors include the proximity to roads, rivers, and towns, land use zoning, and biophysical features, as described by SOARES-FILHO et al., (2006). Using a similar approach, the model also allocated the areas undergoing regrowth in order to meet policy targets, established exogenously to the model.

The third step taken by OTIMIZAGRO involved the spatial allocation of crops and pasture in the deforested areas and the transition between these agricultural land-uses. It was simulated nine annual crops (soy, sugarcane, corn, cotton, wheat, beans, rice, manioc, and tobacco), including single and double-cropping; five perennial crops (Arabic coffee, Robusta coffee, oranges, bananas, and cocoa); and plantation forests. Concurrent allocation and future expansion of crops at 25 ha cell resolution was the function of crop aptitude and profitability calculated by using regional selling prices, production, and transportation costs for each crop. For the expansion of cattle ranching, the model simulated the dynamics of a complete beef production cycle, which included cow-calf, backgrounding, and fattening operations at selected spatial units, *e.g.,* from an individual ranch up to a municipal or regional level. The model *ex-ante* evaluated the effects of management strategies on herd productivity, the system economics, and resulting GHG emissions.

The rate of crops expansion and pastures was defined exogenously by demand projections provided by EFES and MESSAGE models. Since Brazil has 70 Mha of pasture with low occupancy that can be intensified or converted to agriculture, it was not necessary to adjust the deforestation rates in order to meet food demand. In order to take into account changes in deforestation probability and expansion of specific crops following the construction of new roads and frontier expansion, the model ran iteratively, taking as an input the land-use map calculated in the previous year between 2010-2050. Following this procedure, OTIMIZAGRO generated a land-use map transition matrix for each year of the study at a resolution of 500 m^2. Based on land use maps, it was then possible to calculate the GHG emissions and removals from land use, land use change, and forestry (LULUCF) using the emission factors provided by Third National Communication (TCN) of Brazil to the United Nations Framework Convention on Climate Change (MCTIC, 2016).

Based on the areas, GHG emissions, and removals provided by OTIMIZAGRO, it was calculated the net cost of the implantation of GHG mitigation options for the land use and agriculture sector. It involved calculating the investment and operating costs and revenue of planted forests, agriculture, cattle ranching, forest restoration, and deforestation reduction policies in the reference and low carbon scenarios. In this process, it was also considered the emissions and removals of GHG derived from agricultural activities. This involved methane emissions from enteric fermentation and fertilizers, and removals from pasture restoration and direct plantation.

In the case of deforestation policies, it was necessary to calculate the mix of command and control (i.e., law enforcement *in situ* and remotely via the environmental registry, CAR) and payment for environmental services (i.e., CRA market) based on the land tenure and Brazilian Forest Code requirements of each biome.

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