Journal of Global Economic Analysis, Volume 9 (2024), No. 2, pp. 01-69.

GTAP-SIMPLE-G: Integrating Gridded Land Use, Crop Production and Environment Impacts into Global General Equilibrium Model of Trade

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The integration between global and local economic systems has become an increasingly important research topic. This paper presents GTAP-SIMPLE-G, a general-equilibrium framework that extends the existing GTAP model by integrating a gridded partial equilibrium system detailing land use and crop production. This integrated framework links global demand and bilateral trade flows with local level crop supply and land use conversion, accounting for spillover effects across land-using sectors and subnational regions. The paper details the structure of GTAP-SIMPLE-G model, the development of a gridded database for one region in the model – namely Brazil, and the calibration of key parameters that govern the land use conversion and as well as the multi-crop production decisions. For illustrative purposes, GTAP-SIMPLE-G is applied to simulate the impacts of China's retaliatory tariffs on U.S. soybean exports on Brazilian crop production and land use at the local level. Findings show that the tariff shock causes not only an increase in Brazilian soybean production, but also highly heterogeneous responses in the production of other crops as well as land use in the wake of spatially varying multi-crop activities. Finally, this paper discusses the potential extensions of GTAP-SIMPLE-G for future studies and policy assessments on the Global-to-Local-to-Global linkages.

JEL codes: C68, D58, F18, Q15, Q17

Keywords: Computable General Equilibrium Analysis; Global Trade; Spillover Effects; GTAP; Gridded Modeling

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1. Introduction

Understanding the Global-to-Local-to-Global (GLG) linkages in economic models has become an increasingly important topic in the context of sustainable development (Hertel et al., 2023). Historically, computable economic models are usually established at regional or subregional levels.[1] While these models are capable of simulating international trade or domestic socio-economic impacts, they cannot capture the location-specific mechanisms such as spatial spillover effects, mobility of labor and capital and domestic transportation margins, which are critical to fully understand the economic and environmental effects of sustainability challenges and associated policies. In addition to local responses to global drivers (the Global-to-Local linkages), it is equally important to account for global responses to local drivers (the Local-to-Global linkages). For example, conservation policies in one country not only cause spatially heterogeneous impacts on local agricultural production but may also influence other countries through international trade (Torres et al., 2017). Finally, the rapid development of satellite-based spatial datasets on land use, crop cover and crop output has enabled researchers to overcome the gap of data unavailability at finer spatial resolution (see a systematic review by Kim et al. (2021)), which is also fundamental to extending existing economic models to incorporate these GLG linkages.

Such GLG extensions can be achieved with an innovative economic model: GTAP-SIMPLE-G. As its name suggests, GTAP-SIMPLE-G integrates two widely used models for economic and sustainability analysis: the Global Trade Analysis Project (GTAP) model (Corong et al., 2017; Hertel, 1997) and the Simplified International Model of agricultural Prices, Land use and the Environment: Gridded version (SIMPLE-G) (Baldos et al., 2020; Haqiqi and Hertel, 2024). GTAP-SIMPLE-G adopts several important features of the GTAP model, including general equilibrium (GE) closure, bilateral trade flows, multi-product supply system, and accounting relationships taken from input-output tables. Moreover, GTAP-SIMPLE-G disaggregates the land use and crop production in the focus regions from the regional to local level, following the partial equilibrium (PE) structure of SIMPLE-G. GTAP-SIMPLE-G is implemented in the GEMPACK economic modeling software (Horridge et al., 2018).[2] In this paper, Brazil is selected as the focus region, based on the prior work of SIMPLE-G's regionally focused version for Brazil (SIMPLE-G-Brazil) (Wang et al., 2024). Still, it is worth

[1] In this paper, at the global level "region" and "country" are used interchangeably as it is a common practice to aggregate some countries as a single region and model it at the same level of other countries.

[2] Theoretically, all regions in GTAP-SIMPLE-G can be disaggregated to the gridded level. However, it is suggested to only disaggregate the regions of interest (referred to as "focus regions") according to the research scope and design, in order to reduce the burden of obtaining data and parameters and to speed up simulations.

emphasizing that GTAP-SIMPLE-G is a flexible framework that enables the disaggregation of any region where gridded data and parameters are available.

Embedding a gridded land use and crop production system within the GE model allows GTAP-SIMPLE-G to capture both drivers and responses at the spatial level, setting it apart from other models. Researchers have made several attempts to integrate the global and local economic systems (Hertel et al., 2019), including pioneering works such as GTAP-AEZ (Hertel et al., 2008), MAgPIE (Lotze-Campen et al., 2008), GLOBIOM (Havlík et al., 2013), together with their extensions (Table 1).

Table 1. Comparison between GTAP-SIMPLE-G and relevant models

Model	Category	Land use resolution	Solution
MAgPIE	PE	30 arcminutes	Optimization
GLOBIOM	PE	30 arcminutes	Optimization
SIMPLE-G	PE	5 arcminutes	Equilibrium
GTAP-AEZ	GE	AEZ	Equilibrium
GTAP-InVEST	GE	300 meters	Equilibrium
GTAP-SIMPLE-G	GE	5 arcminutes	Equilibrium

Notes: In "Solution" column, "Optimization" means the model is solved by optimizing the objective function; "Equilibrium" means the model is solved as the change of an equilibrium after exogenous shocks.

Source: Hertel et al. (2016) with author edits.

Among these models, GTAP-SIMPLE-G is most similar to GTAP-AEZ and GTAP-InVEST (Johnson, Baldos, et al., 2023). GTAP-AEZ divides the total land endowment in each region into 18 Agro-Ecological Zones (AEZs), based on biophysical conditions including climatic zones and the length of crop growing period. Land within each AEZ behaves as distinct input into a national production function, and land use conversion across sectors only happens within the same AEZ. This framework captures land characteristics and substitution between land types, providing a more realistic representation of land use responses than the basic GTAP framework. It has been successfully applied to research on land-use responses to drivers such as biofuel demand (Hertel et al., 2010), R&D growth (Stevenson et al., 2013) and soybean production (Villoria et al., 2022). However, the production functions for each sector (as opposed to the land input) are only characterized at the national level. Furthermore, the AEZ level disaggregation is often too coarse to capture shocks and responses at finer scales, such as states, counties or natural reserves. In addition, since the AEZs are not required to be contiguous, land use changes within the same AEZ can occur across remote areas, limiting the model's implication for policy assessments and applications. GTAP-InVEST extends the GTAP-AEZ framework by coupling it with two additional models: the SEALS model that downscales land use change from AEZs to the grid cell level and the InVEST model that estimates grid cell level ecosystem service responses to land use changes. The gridded ecosystem services changes are then introduced back to GTAP-AEZ as productivity shocks from environmental aspects. This grid cell level downscaling enables GTAP-InVEST to better capture spatial heterogeneity in land use projection than GTAP-AEZ. However, the economic activities in GTAP-InVEST are still resolved at the AEZ level. The SEALS step is a mechanical downscaling exercise. Therefore, the market linkages and commodity mobility between grid cells within each AEZ are still not accounted for in this model.

Similar to GTAP-AEZ and GTAP-InVEST, GTAP-SIMPLE-G inherits the economy-wide sectors and bilateral trade systems from GTAP, while disaggregating the land input to the local level to capture its spatial heterogeneity. On the other hand, GTAP-SIMPLE-G differs from these models in that it solves both land use allocation and multiple crop production at the grid cell level with location-specific production functions. This gridded resolution facilitates a direct connection between GTAP-SIMPLE-G and biophysical and ecological models; it also enables simulation of policies and other external shocks at various spatial scales according to research needs. More importantly, GTAP-SIMPLE-G captures spillover effects across both spatial and sectoral dimensions. When a policy is implemented in one area, its effects often extend to other areas connected within the same market, as well as other markets, through price linkages. Although these spillover effects have been identified empirically, they have not been adequately captured by CGE models, especially at fine spatial scale. Insufficient consideration of these spillover effects may cause unintended outcomes of policy implementation (Johnson, Brown, et al., 2023). For example, conservation policies in the Brazilian Amazon biome may shift cropland demand to adjacent states, exacerbating deforestation elsewhere (Dou et al., 2018). In addition, a common challenge in policy evaluation is that the impact of domestic policy may interact with shocks from global markets (Taheripour et al., 2019), requiring the GLG integration in GE models. In contrast, PE models can simulate agricultural sectors with spatial details and gridded interactions. However, they often oversimplify the interdependence of upstream and downstream sectors, thereby limiting their capacity to evaluate cross-sectoral impacts (Hertel, 2000). To address these gaps, GTAP-SIMPLE-G integrates the multi-sector framework of GTAP with the gridded agricultural system of SIMPLE-G to track the transmission of external shocks across both spatial scales and sectors. This integration provides a more comprehensive and realistic assessment of economic, political and environmental drivers.

To illustrate the model’s capacity in analyzing GLG connections, in this paper GTAP-SIMPLE-G is applied to assess how China’s retaliatory tariff on the US soybeans export influences crop production and land use in Brazil.[3] The soybean tariff has been a heated research topic in the wake of US-China trade disputes, with most studies focusing on its direct impacts on the US and China (e.g., Li et al (2019); Itakura (2020)). However, the impact of the US-China soybean tariff extends beyond these two countries and has generated significant spillover effects on soybean-producing countries such as Brazil, due to China's increased demand for non-US soybeans (Dhoubhadel et al., 2023). As a result, Brazil's soybean production has reached record highs in recent years (Colussi et al., 2024). These studies contribute to literature by examining spillover effects from the international market to the national level. However, the driver of increased soybean demand from China also causes spatially heterogeneous impacts across Brazil, affecting not only soybeans but also other crops. This driver also influences land use patterns, including shifts between cropland, pasture and forest, with significant environmental implications. Evaluating tariff impacts at finer spatial scale is crucial but remains under-addressed (Adjemian et al., 2021). Therefore, revisiting this topic with GTAP-SIMPLE-G allows for demonstrating the importance of integrating GLG linkages between local level economic mechanisms, such as farmers' crop production and land use decisions and subnational spillover effects on the one hand, and global trade policy analysis on the other.

The rest of this paper is structured as follows. Section 2 describes the model structure and key components of the GLG framework in GTAP-SIMPLE-G. Section 3 details the development of the gridded database, taking Brazil as an example. Researchers working with subregional models often face challenges in obtaining spatially heterogenous parameters. To address this problem, section 4 introduces a method of simultaneously calibrating multiple subregional parameters using a derivative-free algorithm to obtain multi-cropping and land use conversion parameters for use in the subsequent simulations. Section 5 demonstrates GTAP-SIMPLE-G's ability to undertake GLG analysis with an illustrative assessment of the US-China soybean tariff's impact on Brazil's crop output and land use at the local level. Section 6 discusses the implications, limitations, potential extensions and future directions for GTAP-SIMPLE-G. Finally, section 7 concludes this paper. The current version of GTAP-SIMPLE-G is available in the supplementary material for download, permitting readers to replicate, extend and apply the GTAP-SIMPLE-G model in their own research.

2. Description of GTAP-SIMPLE-G

The GTAP-SIMPLE-G framework consists of two distinct levels: the regional/global level, which models demand and supply for each region (except

[3] In this study and the current version of this model, "China" refers specially to mainland China.

for crop production in the focus region), along with bilateral trade flows between regions; and the local level, which focuses on land use and crop production at the grid cell level within the focus region. The global/regional level structure is based on the standard GTAP model (version 7), as documented in Corong et al.(2017). In view of that, this section provides a brief overview of the global/regional level structure before focusing on the local level structure in detail.

2.1 Model structure on the global/regional level

Figure 1 provides a visual overview of GTAP-SIMPLE-G's structure. Taking a specific region as an example (Figure 1A), producers in each sector decide the use of primary factors such as labor, capital, and land (EVOS), as well as intermediate inputs sourced either domestically (VDFP) or from imports (VMFP). These inputs are utilized to produce commodities, which are supplied to private households (VDPP), government purchase (VDGP), investment (VDIP) feeding into saving (SAVE), and foreign regions (VXSB). All taxes and the revenue received from supplying primary factors are aggregated at the regional level as the income of the regional household. This income is subsequently allocated to private households, government expenditure, and savings, with the aim of maximizing regional utility.

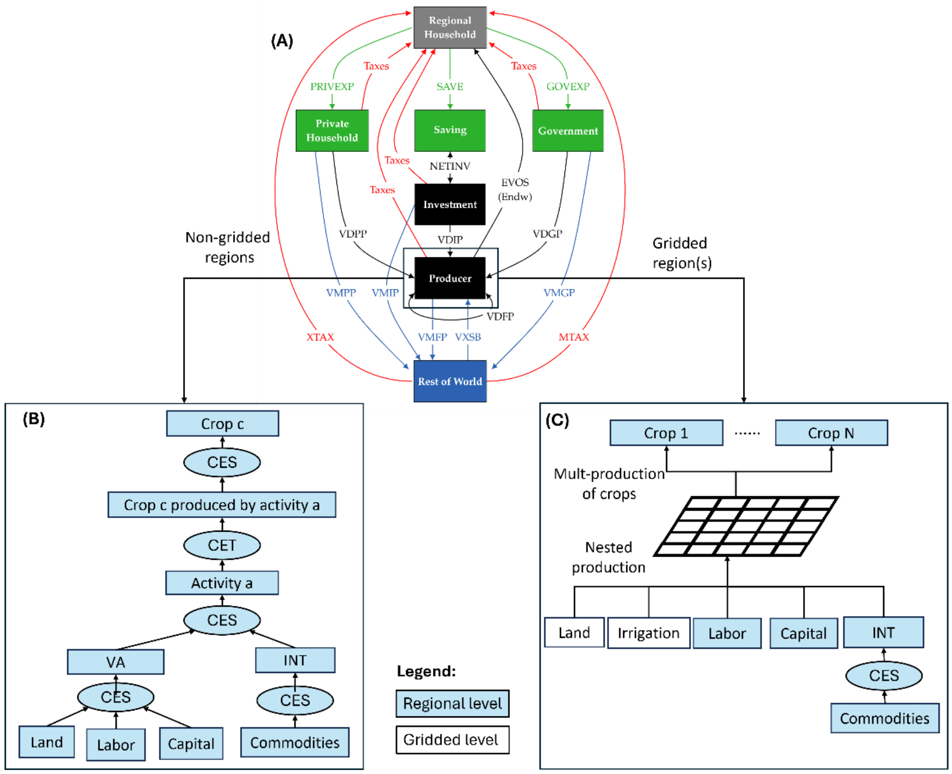

Figure 1. The structure of GTAP-SIMPLE-G model: an overview. (A) The multi-region GTAP framework. Arrows refer to monetary flows (these run in the opposite direction of material flows). (B) The crop production system in non-gridded regions. (C) The crop production system in the gridded region(s). Squares refer to variables in the model and ellipses refer to production functions.

Source: (A) Corong et al. (2017); (B) and (C): Author illustration.

GTAP-SIMPLE-G inherits two key features from the standard GTAP model on the producer side: the nested production system and the distinction between commodities and sectors (which are referred to as "activities" in the GTAP model) (Figure 1B). For non-gridded regions, the nested production system consists of two layers, relying on the assumption of separability in production to allow for modeling production as a multistage process (Berndt and Christensen, 1973). At the lower layer, producers aggregate multiple primary factors to form a composite input named the "value added input" (VA). They also aggregate commodities used in production into another composite input named the "intermediate input" (INT).[4] At the upper layer, producers use both VA and INT to produce the output

[4] Each commodity here is a composite of that commodity produced domestically or by other regions using the Armington assumption, which is not shown in Figure 1B.

of this activity. The constant elasticity of substitution (CES) function governs both layers, allowing for various substitutability across layers and activities. This system relieves the requirement of price-elasticity parameters for each pair of primary factors and commodities. For the gridded region, both the nested production system and land use allocation is extended to the grid cell level (Figure 1C), which is further explained in the following section.

The standard GTAP model also introduces a multi-output production system, which relieves the restriction from the classic GTAP model (version 6.2) that each commodity is produced by a unique, single activity. The multi-output production system consists of two layers, named "make" and "sourcing", bridging activities and commodities. At the "make" layer, a constant elasticity of transformation (CET) function is used to allocate the output of an activity to one or more commodities. While at the "sourcing" layer, a CES function aggregates a certain commodity produced by one or more activities. Under the default setting of the standard GTAP framework, commodities produced by different sectors are assumed to be perfect substitutes, which simplifies the CES function to a linear function. This multi-output production system enables users to model multiple commodities produced from the same activity, for example soybean oil and soybean meal from the soybean crushing activity. Alternatively, this system also allows the same commodity to be produced from different activities, for example electricity produced by sectors using fossil fuel or renewable energy (Corong et al., 2017). In GTAP-SIMPLE-G, the multi-output production system is applied to produce eight GTAP crops from a single "cultivation" activity at both regional and gridded levels, to overcome the lack of data on crop-specific gridded input usage and to enable multi-cropping in the nested production system.

2.2 Model structure on the local level

In the focus region, GTAP-SIMPLE-G extends the land use and crop production systems from the GTAP framework to the local level with an enhanced nested structure, as shown in Figure 2. This local structure consists of five types of layers: CES, CET, quantity-preserving CES (QCES), quantity-preserving CET (QCET), and perfect mobility (PM). CES and CET functions maintain the total value between inputs and outputs, ensuring zero-profit condition in crop production system. On the other hand, they do not preserve the total quantity between inputs and outputs, which is essential for tracking land use and crop outputs from the bio-physical aspects. Therefore, QCES and QCET functions are employed in the allocation of land and the gridded – regional aggregation of crops (van der Mensbrugghe and Peters, 2020). GTAP-SIMPLE-G defines intermediate inputs, labor and capital as mobile inputs across both activities and space, although this assumption could be modified as in Ray et al. (2023). The PM layer ensures that the price of each mobile input remains uniform across grid cells, and the total quantity used locally equals the regional total. For ease of model simulation, all layers are expressed as equations in percentage change form. Detailed mathematical notes on these layers' functional forms and derivation of their percentage change form solutions are available in Appendix A.

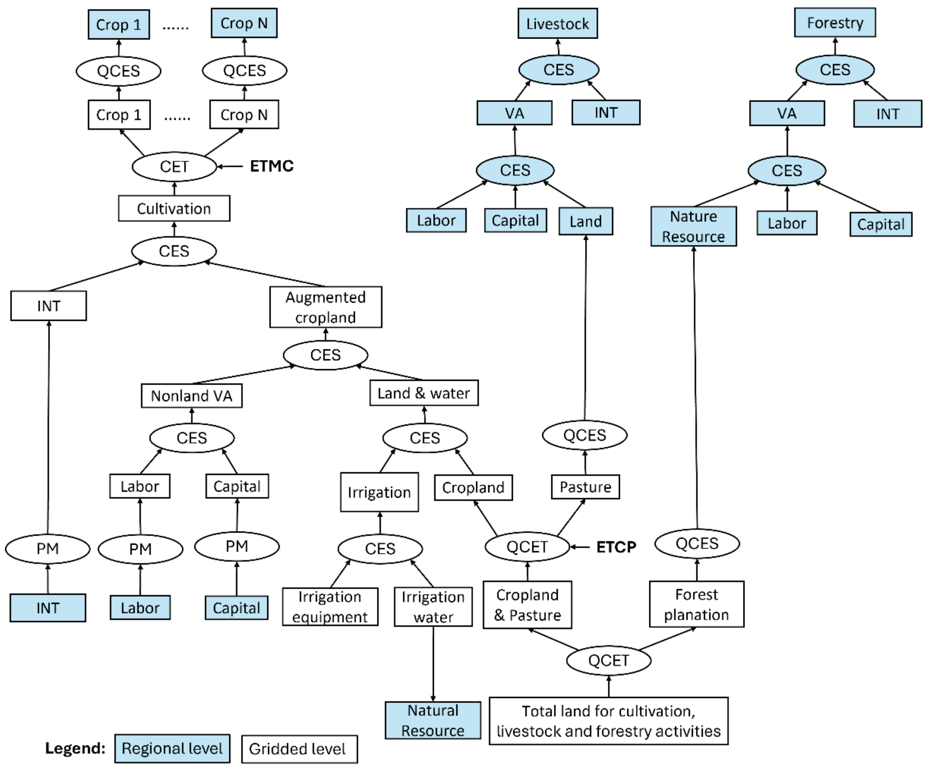

Figure 2. The structure of GTAP-SIMPLE-G model in the gridded region. Squares refer to variables and ellipses refer to functions.

Source: Author illustration.

The first major extension of GTAP-SIMPLE-G beyond SIMPLE-G is an enhanced multi-purpose land use system at the local level (Listing 1). Each grid cell is endowed with the baseline land area, which is equal to the sum of forest plantation, pasture and cropland. Land allocation, in response to relative rental rates, is modeled with a two-layer QCET structure: the first layer allocates land between the cropland-pasture composite and the forest plantation, while the second layer distinguishes between cropland and pasture. Since pasture–cropland conversion is the primary pattern observed in land use change in Brazil, this structure captures its transformability at the local level with a specific parameter: the elasticity of transformation between cropland and pasture (ETRACPg, or ETCP). Once land use allocation is complete, the pasture and forest planation areas are aggregated to the regional level with CES functions, serving as land inputs to the national level livestock and forestry activities. This is the way the GTAP-AEZ model operates. On the other hand, cropland areas remain at the grid cell level as inputs for the gridded crop production functions.

In the current version, changes in other land use categories, including natural forest, commercial and residential land, and land unsuitable for cultivation, are all treated as exogenous variables. While natural forest is integral to land use patterns and conversions, a substantial component of its value belongs to the ecosystem services it provides, which are not monetized nor included in the utility function of the regional household. If the non-market value of natural forest is overlooked, its rent would be underestimated, leading to excessive deforestation in simulations. To prevent this, the GTAP-SIMPLE-G model treats natural forest land change (such as from conservation policies) as an exogenous adjustment to the total land endowment. This can be used to account for land use policies for forest conservation and agricultural production (e.g. Brazil’s Forest Code and Native Vegetation Protection Law (Metzger et al., 2019)). Similarly, changes in commercial and residential land areas, as well as land unsuitable for cultivation, are also modelled exogenously since the demand for those land use categories is not captured in the model.

Listing 1. GEMPACK equations for gridded land use allocation.[5]

```
! Allocation: cropland and pasture !
Equation E_QLANDg  (all,g,GRID)
p_QLANDg(g)
    = p_QCPLANDg(g)
    - ETRACPg(g) * [p_PLANDg(g) - p_PCPLCOMg(g)];

Equation E_QPLANDg  (all,g,GRID)
p_QPLANDg(g)
    = p_QCPLANDg(g)
    - ETRACPg(g) * [p_PPLANDg(g) - p_PCPLCOMg(g)];

! Calculate quantity-based composite price !
E_PCPLCOMg      (all,g,GRID)
p_PCPLCOMg(g) =
    SHRQLANDg(g) * p_PLANDg(g) + SHRQPLANDg(g) * p_PPLANDg(g) ;

! Linearization of zero-profit condition!
E_PCPLANDg      (all,g,GRID)
p_PCPLANDg(g) + p_QCPLANDg(g) =
    SHRVLANDg(g) * [p_PLANDg(g) + p_QLANDg(g)] +
    SHRVPLANDg(g) * [p_PPLANDg(g) + p_QPLANDg(g)] ;

! Allocation: cropland & pasture and forest !
```

[5] In GTAP syntax, the level form of a variable and its percentage change form are represented by uppercase and lowercase letters respectively. In SIMPLE-G syntax, the percentage change from of a variable is represented by adding a prefix “p_” before the level form of a variable. In GTAP-SIMPLE-G, both syntaxes are used because they help researchers to distinguish between global and local level variables in both the source code and simulation results. A complete listing of names, dimensions and descriptions of the variables and parameters introduced in GTAP-SIMPLE-G is available in Appendix B.

```
Equation E_QCPLANDg  (all,g,GRID)
p_QCPLANDg(g) = p_QTLANDg(g)
    - ETRAFCPg(g) * [p_PCPLANDg(g) - p_PTLCOMg(g)];

Equation E_QFORESTg  (all,g,GRID)
p_QFORESTg(g)
    = p_QTLANDg(g)
    - ETRAFCPg(g) * [p_PFORESTg(g) - p_PTLCOMg(g)];

! Calculate quantity-based composite price !
E_PTLCOMg      (all,g,GRID)
p_PTLCOMg(g) =
    SHRQCPLANDg(g) * p_PCPLANDg(g) + SHRQFORESTg(g) * p_PFORESTg(g) ;

! Linearization of zero-profit condition!
E_PTLANDg      (all,g,GRID)
p_PTLANDg(g) + p_QTLANDg(g) =
    SHRVCPLANDg(g) * [p_PCPLANDg(g) + p_QCPLANDg(g)] +
    SHRVFORESTg(g) * [p_PFORESTg(g) + p_QFORESTg(g)] ;
```

The second major extension of GTAP-SIMPLE-G is the gridded crop production system (Listings 2 and 3). First, all eight crop-producing activities (rice, wheat, oilseeds, other grains, sugar crops, vegetable & fruits, plant-based fibers, other crops) in GTAP are aggregated into a single activity named "cultivation". This aggregation helps researchers to overcome the unavailability of crop-specific input use data at the grid cell level. [6] For each grid cell, the cultivation activity is modeled with an enhanced nested CES system, with two parallel subsystems based on irrigation types: irrigated and rainfed cultivation. In the irrigated cultivation subsystem, two new inputs -irrigation water (both surface water and groundwater) and irrigation equipment – are introduced to form a composite input named "irrigation". This composite input is then combined with the irrigated cropland to form another composite input "land and water". While in the rainfed cropland subsystem, the rainfed cropland input is equivalent with the "land and water" input as its water supply has no cost. These subsystems enable simulation of drivers related to climate change, such as variations in water supply and/or yield loss due to insufficient water. In the original SIMPLE-G framework, the supply of irrigation water and irrigation equipment are represented by partial-equilibrium style supply functions, which link quantity and price changes with location-specific supply elasticities. To be consistent with the general equilibrium framework of GTAP, the supply of irrigation water is defined exogenously at grid

[6] To facilitate the connection of input data between the gridded and regional level, the aggregation from eight crop producing activities to the single cultivation activity is also applied to the regional database from GTAP. Upon the availability of better gridded crop-specific input data, it is possible to model crop-specific producing activities at the grid cell level as well.

cell level as the natural resource input used in cultivation, while the irrigation equipment is merged with the capital input for use in cultivation activity.[7]

Listing 2. GEMPACK equations for gridded cropland allocation between irrigation subsystems.

```
! Allocation: irrigated and rainfed cropland!
Equation E_PLANDgl  (all,g,GRID)(all,l,LTYPE)
p_QLANDgl(g,l)
    = p_QLANDg(g)
    - ETRALANDg(g) * [p_PLANDgl(g,l) - p_PLCOMg(g)];

! Calculate quantity-based composite price !
E_PLCOMg       (all,g,GRID)
p_PLCOMg(g) =
    sum(l,LTYPE, SHRQLANDgl(g,l) * p_PLANDgl(g,l)) ;

! Linearization of zero-profit condition!
E_PLANDg       (all,g,GRID)
p_PLANDg(g) + p_QLANDg(g) =
    sum(l,LTYPE, SHRVLANDgl(g,l) * [p_PLANDgl(g,l) + p_QLANDgl(g,l)]) ;
```

In both subsystems, labor and capital inputs are disaggregated from the regional level down to the grid cell level with PM layers. They form the composite input of "non-land value added" (nonland VA). Next, the nonland VA is combined with the "land and water" input to form the composite input named "augmented land". This input represents the combination of primary factors used in cultivation. At the top layer of the cultivation activity, the INT inputs, which are disaggregated at the grid cell level with PM layers, are combined with the augmented land input. Together, they produce the output of the cultivation activity as the composite of crops, within both irrigated and rainfed subsystems.

Listing 3. GEMPACK equations for the gridded cultivation activity.

```
! Layer: irrigation water + irrigation equipment  -> irrigation !
Equation E_QWATSGgl  (all,g,GRID)(all,l,LTYPE)
p_QWATSGgl(g,l)
     = p_QWATERgl(g,l) - p_AFWATSG(g,l)
    - ESUBWgl(g,l)  * [p_PWATSGgl(g,l) - p_AFWATSG(g,l) - p_PWATERgl(g,l) ] ;

Equation E_QWATEQgl    (all,g,GRID)(all,l,LTYPE)
p_QWATEQgl(g,l)
     = p_QWATERgl(g,l) - p_AFWATEQ(g,l)
     - ESUBWgl(g,l)    * [p_PWATEQgl(g,l) - p_AFWATEQ(g,l) - p_PWATERgl(g,l) ]
;
```

[7] In the current version, the value of irrigation equipment input is combined with the value of capital input at grid cell level, and the supply elasticity of irrigation equipment is set to be a tiny value close to zero, which disables the irrigation equipment input in the current version. The irrigation water – equipment structure is preserved for future extensions (Haqiqi, Bowling, et al., 2023).

```
Equation E_PWATERgl     (all,g,GRID)(all,l,LTYPE)
p_PWATERgl(g,l)
     = SHR_SGinWgl(g,l) * [p_PWATSGgl(g,l) - p_AFWATSG(g,l)]
     + SHR_EQinWgl(g,l) * [p_PWATEQgl(g,l) - p_AFWATEQ(g,l)];
! Layer: land + irrigation -> landwater !
Equation E_QLANDgl     (all,g,GRID)(all,l,LTYPE)
p_QLANDgl(g,l)
     = p_QLANDWTRgl(g,l) - p_AFLAND(g,l)
     - EIRRIGgl(g,l)   * [p_PLANDgl(g,l) - p_AFLAND(g,l) - p_PLANDWTRgl(g,l) ];

Equation E_QWATERgl  (all,g,GRID)(all,l,LTYPE)
p_QWATERgl(g,l)
     = ISIRRI(l) * p_QLANDWTRgl(g,l) - ISIRRI(l) * p_AFWATER(g,l)
     - ISIRRI(l) * EIRRIGgl(g,l) * [p_PWATERgl(g,l) - p_AFWATER(g,l) -
     p_PLANDWTRgl(g,l) ] ;

Equation E_PLANDWTRgl  (all,g,GRID)(all,l,LTYPE)
p_PLANDWTRgl(g,l)
     = SHR_LinLWgl(g,l) * [p_PLANDgl(g,l)  - p_AFLAND(g,l)]
     + SHR_WinLWgl(g,l) * [p_PWATERgl(g,l) - p_AFWATER(g,l)]  ;

! Layer: labor + capital -> nland !
Equation E_QLABORgl    (all,g,GRID)(all,l,LTYPE)
p_QLABORgl(g,l)
     = p_QNLANDgl(g,l)  - p_AFLABOR(g,l)
     - ENLANDgl(g,l) * [p_PLABORgl(g,l) - p_AFLABOR(g,l)  - p_PNLANDgl(g,l) ]
;

Equation E_QCAPgl    (all,g,GRID)(all,l,LTYPE)
p_QCAPgl(g,l)
     = p_QNLANDgl(g,l)  - p_AFCAP(g,l)
     - ENLANDgl(g,l) * [p_PCAPgl(g,l) - p_AFCAP(g,l)  - p_PNLANDgl(g,l) ]  ;

Equation E_PNLANDgl  (all,g,GRID)(all,l,LTYPE)
p_PNLANDgl(g,l)
     = SHR_LinNLgl(g,l) * [p_PLABORgl(g,l)  - p_AFLABOR(g,l)]
     + SHR_CinNLgl(g,l) * [p_PCAPgl(g,l) - p_AFCAP(g,l)]  ;

! Layer: landwater + nland -> augland !
Equation E_QLANDWTRgl  (all,g,GRID)(all,l,LTYPE)
p_QLANDWTRgl(g,l)
     = p_QAUGLANDgl(g,l)
     - EAUGLANDgl(g,l) * [p_PLANDWTRgl(g,l) - p_PAUGLANDgl(g,l) ] ;

Equation E_QNLANDgl  (all,g,GRID)(all,l,LTYPE)
p_QNLANDgl(g,l)
     = p_QAUGLANDgl(g,l)
     - EAUGLANDgl(g,l) * [p_PNLANDgl(g,l) - p_PAUGLANDgl(g,l) ] ;

Equation E_PAUGLANDgl  (all,g,GRID)(all,l,LTYPE)
p_PAUGLANDgl(g,l)
     = SHR_LinAUGgl(g,l) * [p_PLABORgl(g,l) - p_AFLABOR(g,l)]
     + SHR_CinAUGgl(g,l) * [p_PCAPgl(g,l) - p_AFCAP(g,l)]
     + SHR_DinAUGgl(g,l) * [p_PLANDgl(g,l) - p_AFLAND(g,l) ]
     + SHR_WinAUGgl(g,l) * [p_PWATERgl(g,l)- p_AFWATER(g,l)] ;

! Layer: augland + int -> crop !
Equation E_QAUGLANDgl  (all,g,GRID)(all,l,LTYPE)
p_QAUGLANDgl(g,l)
     = p_QCROPgl(g,l)  - p_AOCROP(g,l)
     - ECROPgl(g,l)* [p_PAUGLANDgl(g,l) - p_PCROPgl(g,l) - p_AOCROP(g,l)] ;

Equation E_QINTgl    (all,g,GRID)(all,l,LTYPE)
```

```
p_QINTgl(g,l) + p_AFINT(g,l)
     = p_QCROPgl(g,l)  - p_AOCROP(g,l)
     - ECROPgl(g,l)* [p_PINTgl(g,l) - p_AFINT(g,l) -
                      p_PCROPgl(g,l)  - p_AOCROP(g,l) ];

Equation E_PCROPgl     (all,g,GRID)(all,l,LTYPE)
p_PCROPgl(g,l) + p_AOCROP(g,l)
     = SHR_LANDgl(g,l)  * [p_PLANDgl(g,l)  - p_AFLAND(g,l)]
     + SHR_INTgl(g,l)   * [p_PINTgl(g,l)   - p_AFINT(g,l)]
     + SHR_LABORgl(g,l) * [p_PLABORgl(g,l) - p_AFLABOR(g,l)]
     + SHR_CAPgl(g,l)   * [p_PCAPgl(g,l)   - p_AFCAP(g,l)]
     + SHR_WATSGgl(g,l) * [p_PWATSGgl(g,l) - p_AFWATSG(g,l)]
     + SHR_WATEQgl(g,l) * [p_PWATEQgl(g,l) - p_AFWATEQ(g,l)] ;
```

Following the standard GTAP framework, GTAP-SIMPLE-G also introduces a multi-crop production system that bridges the cultivation activities at gridded level with the crop output at regional level. For each subsystem at the grid cell level, the composite cultivation activity is allocated to eight GTAP crop commodities based on their baseline data and relative price changes. The multi-crop production is governed by a CET function and its elasticity of transformation across multiple crops (ETRANSMC, or ETMC). Since crops produced in different locations may not be perfect substitutes, the outputs from both subsystems across all grid cells are aggregated with a QCES function at the regional level under the Armington assumption, which differentiates commodities by their sources.

Listing 4. GEMPACK equations for the gridded multiple crop production system.

```
! CET allocation from aggregated crop to multiple crops !
Equation E_QMCROPglc (all,g,GRID)(all,l,LTYPE)(all,c,CROP)
p_QMCROPglc(g,l,c) = p_QCROPgl(g,l) - p_AFQMCROPgc(g,c) -
ETRANSMC(g,l) * [p_PMCROPglc(g,l,c) - p_AFQMCROPgc(g,c) - p_PCROPgl(g,l)];

Equation E_PMCROPglc (all,g,GRID)(all,l,LTYPE)
p_PCROPgl(g,l) = sum(c, CROP, SHRVMCROPglc(g,l,c) * p_PMCROPglc(g,l,c));

! QCES Aggregation from gridded multicrop to regional multicrop !
Equation E_QMCROPrc (all,g,GRID)(all,l,LTYPE)(all,c,CROP)
p_QMCROPglc(g,l,c) = p_QMCROPrc(GRID2GREG(g),c)
- ESUBMC(GRID2GREG(g),c)*[p_PMCROPglc(g,l,c)-p_PMCRPCOMrc(GRID2GREG(g),c)];

Equation E_PMCRPCOMrc (all,r,GREG)(all,c,CROP)
p_PMCRPCOMrc(r,c) =
sum(g, GRID: GRID2GREG(g) EQ r, sum(l, ltype,
SHRQMCGLinR(g,l,c)*p_PMCROPglc(g,l,c)));

Equation E_PMCROPrc (all,r,GREG)(all,c,CROP)
p_QMCROPrc(r,c) + p_PMCROPrc(r,c) =
sum(g, GRID: GRID2GREG(g) EQ r, sum(l, ltype, SHRVMCGLinR(g,l,c)*
    (p_QMCROPglc(g,l,c) + p_PMCROPglc(g,l,c))));
```

Finally, all gridded land use allocations, as well as inputs for cultivation and multiple crop outputs are aggregated to the regional level and connected with the corresponding price and quantity changes in the GTAP framework (Listing 5). These connections link the gridded land use and cultivation systems with the global trade and demand systems as illustrated in Figure 1, while also preserving the price and quantity homogeneity in the general equilibrium of economy.

Listing 5. GEMPACK equations of connections between gridded and national levels.

```
! Connect input price and quantity changes used in cultivation act. a in
gridded region r !
Equation E_pfe_gc_labor (all,r,GREG)
pfe("Labor","Cultivation",r) = p_PLABORr(r);

Equation E_qfe_gc_labor (all,a,CACT)(all,r,GREG)
qfe("Labor",a,r) = p_QLABORr(r);

Equation E_pfe_gc_cap (all,r,GREG)
pfe("Capital","Cultivation",r) = p_PCAPr(r);

Equation E_qfe_gc_capital (all,a,CACT)(all,r,GREG)
qfe("Capital",a,r) = p_QCAPr(r);

Equation E_PINTr (all, r, GREG)
pint("Cultivation",r) = p_PINTr(r);

Equation E_qint_gc (all,a,CACT)(all,r,GREG)
qint(a,r) = p_QINTr(r);

Equation E_pes2_gc (all,e,ENDWS)(all,a,CACT)(all,r,GREG)
pfe(e,a,r) = p_PLANDr(r);

Equation E_qfe_gc_land (all,a,CACT)(all,r,GREG)
qfe("Land",a,r) = p_QLANDr(r);

Equation E_QWATSGsup (all,r,GREG)
qesf("NatRes","Cultivation",r) = p_QWATSGr(r);

Equation E_PWATSGsup (all,r,GREG)
pfe("NatRes","Cultivation",r) = p_PWATSGr(r);

! Connect price and quantity changes in crop commodity c produced by
cultivation act. a in gridded region r !

Equation E_PMCROPrc_ps (all,r,GREG)(all,c,CROP)
ps(c,"Cultivation",r) = p_PMCROPrc(r,c);

Equation E_qca_gc_c (all,c,CROP)(all,a,CACT)(all,r,GREG)
qca(c,a,r) = p_QMCROPrc(r,c);

! Connect price and quantity changes in pasture and forest plantation in
gridded region r !

Equation E_QFORESTsup (all,r,GREG)
qesf("NatRes","Forestry",r) = p_QFORESTr(r);

Equation E_PFORESTsup (all,r,GREG)
pfe("NatRes","Forestry",r) = p_PFORESTr(r);

Equation E_QWATSGsup (all,r,GREG)
qesf("NatRes","Cultivation",r) = p_QWATSGr(r);

Equation E_PWATSGsup (all,r,GREG)
pfe("NatRes","Cultivation",r) = p_PWATSGr(r);
```

3. Establishment of model database

The GTAP-SIMPLE-G database contains two components for the global and local structures respectively. At the global level, it uses the GTAP version 11 database, which is benchmarked to the base year 2017 (Aguiar et al., 2022). This database provides the necessary data and parameters on regional supply, demand, and bilateral trade flow across regions. The original GTAP database includes 65 commodities, 65 activities, 8 primary factors, and 160 regions. For the purpose of this study, it was aggregated to 29 commodities, 22 activities (with all eight crop-producing activities combined into the “cultivation” activity), 4 primary factors, and 13 regions. This aggregation preserves regions and activities of interest while simplifying the database for more efficient calculation. The mapping between GTAP and GTAP-SIMPLE-G databases is available in Appendix C (Table C.1-C.4).

At the local level, researchers need to establish a database of gridded land use, agricultural inputs, and crop production data tailored to their specific research objectives. In this study, Brazil is selected as the focus region and the spatial resolution of grid cells is set to five arcminutes, ensuring the consistency with existing data sources.[8] The process of creating the local level database for Brazil also serves to provide guidelines for generalizing GTAP-SIMPLE-G to other regions. The workflow of creating the local level database for Brazil is summarized in Figure 3 and explained in detail in following subsections. For additional discussions on the selection of land use and crop output database, please refer to Appendix D.

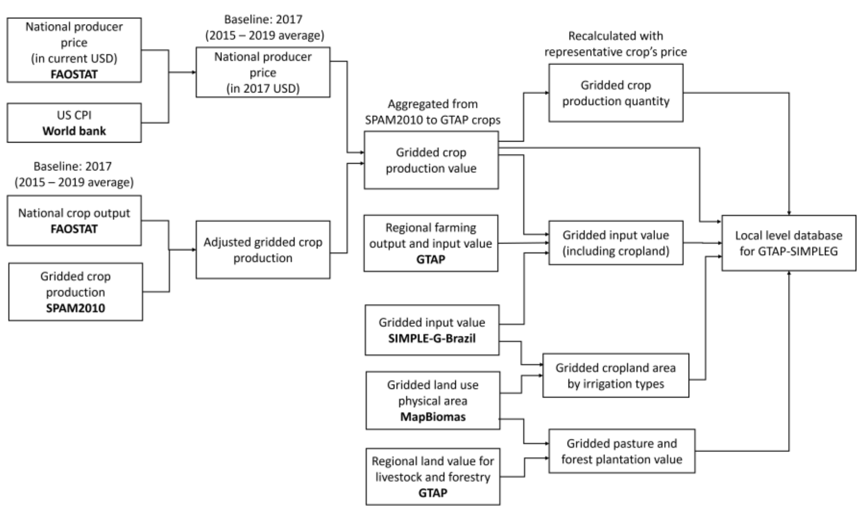

Figure 3. Workflow to create the local level database. Bold text indicates the source of data.

Source: Author illustration.

[8] The total physical area of each grid cell is roughly 7000 – 8000 hectares in Brazil.

3.1 Land use

The gridded land use data in Brazil are obtained from MapBiomas, collection 8 (2023). MapBiomas contains Brazilian land use data since 1985 at a spatial resolution of 30 meters. Compared with gridded datasets that focus solely on cropland (Thenkabail et al., 2021; Tang et al., 2024), MapBiomas includes land use data for natural forest, forest plantation, and pasture, which are necessary for modeling land use conversion in GTAP-SIMPLE-G.

The processing of MapBiomas data is divided into three steps. First, to be consistent with the GTAP database, the land use data in 2017 were accessed through the "MapBiomas collection" plugin in QGIS (version 3.22) as a raster of pixels with categorical values at a 30-meter resolution, assigning each pixel to a single land use category. Second, the original MapBiomas land use categories were aggregated into eight categories: natural forest, forest plantation, non-forest vegetation, pasture, cropland, urban infrastructure, other non-vegetated area, and water. This aggregation reduced the data size and facilitated data processing; the aggregation criteria is available in Appendix C (Table C.4). Next, a grid at 5-arcmin resolution was created for Brazil, and the total number of pixels for each category per grid cell was calculated with the "zonal histogram" function. Finally, the physical area of each land use categories in hectares (ha) at grid cell level was calculated with:

$$AREA_{i,j} = AREA_i \frac{COUNT_{i,j}}{\sum_{k=1}^{8} COUNT_{i,k}} \tag{1}$$

where i is the index of grid cell, j is the index of each new land use category. In grid cell i, $AREA_i$ refers to its physical area, $COUNT_{i,j}$ refers to the number of pixels that belongs to category j, and $AREA_{i,j}$ refers to the physical area of category j in that grid cell. Following this approach, the gridded land use data was established for eight categories over 103,751 grid cells, shown in Appendix D (Figure D.1). The cropland, pasture and forest plantation areas are included in the GTAP-SIMPLE-G database, while the data for other categories can be used to design experiments relevant with exogenous land use change.

In addition to the area of cropland, pasture, and forest plantation, the database also requires their monetary values at the grid cell level. To be consistent with the GTAP database, the regional value of land input used in livestock production activities was disaggregated with the physical area of pasture from MapBiomas as the spatial pattern. Similarly, the regional value of natural resource factor used in forestry activity was disaggregated according to the spatial pattern of forest plantation. The processing of disaggregated cropland value is detailed in section 3.3, along with other cultivation inputs. Future work would benefit from more spatially resolved estimates of productivity for pastures and forests.

3.2 Crop production

The gridded output database for multiple crops is developed based on the gridded output data from SPAM2010 (Yu et al., 2020) and national output data from FAOSTAT database (Food and Agriculture Organization of the United Nations, 2023). SPAM2010 provides global gridded output data for 42 crops by irrigation types in 2010, at a resolution of 5 arcminutes. This data is used to disaggregate the national data from FAOSTAT to grid cell level, by irrigation types.

The processing of the gridded crop production database includes four steps. First, Brazil's crop production (in metric tons) and producer price (in US dollars per metric ton) were collected from the FAOSTAT database for the 2017 base year.[9] To mitigate short-term fluctuations, a five-year average from 2015 to 2019 was calculated for each crop to represent the 2017 baseline data for both outputs and price. Second, the national crop production data were disaggregated to grid cells by irrigation type, using output data from SPAM2010 to provide the spatial pattern. To aggregate across crop categories, it is necessary to convert quantity-based production data to value terms. In the third step, the gridded output values for SPAM2010's 42 crops were calculated from its quantity and price, then aggregated into the eight GTAP crop categories. The mapping between FAOSTAT, SPAM2010 and GTAP is available in Appendix C (Table C.5), while the gridded crop output values for GTAP crops are presented in Appendix D (Figure D.2).

3.3 Cultivation inputs

In addition to land use and crop production, the gridded GTAP-SIMPLE-G database requires inputs for cultivation activity at the grid cell level. The database of SIMPLE-G-Brazil model (Wang et al., 2024) provides the usage (both quantity and value) for five inputs: fertilizer, land, irrigation water, irrigation equipment, and other inputs including labor and capital, at a resolution of 5 arcminute in 2017. One notable disparity between these two models is that labor and capital are treated as two separate inputs in GTAP-SIMPLE-G, while they are aggregated into "other inputs" in SIMPLE-G-Brazil. Thus, the cost share of labor in Brazilian agriculture (Lima, 2017) is utilized to allocate "other inputs" into labor and capital.[10] Another disparity is that, in order to align with the GTAP database, the production system for cultivation must include intermediate inputs, which are not available in the gridded database of SIMPLE-G-Brazil or other datasets. To address this issue, the cost of intermediate inputs is represented by fertilizer usage, which constitutes the majority of intermediate input costs in Brazil (Colussi et al., 2024).

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[9] In GTAP-SIMPLE-G, all monetary terms were converted to 2017 US dollars based on the US's consumer price index (World Bank, 2024).

[10] The cost share data are available at subdivision level (north, northeast, center-west, southeast and south). For each grid cell, the cost share from its associated subdivision was applied to distinguish between labor and capital.

3.4 Connection between gridded and regional database

For each focus region, the gridded input and output values in the cultivation activity need to be consistent with the regional level value from the GTAP database to avoid violating Walras Law. For each grid i and irrigation type l, the zero-profit condition for cultivation is expressed as follows:

$$\sum_{c} VMCROP_{i.l,c} = VCROP_{i.l} = \sum_{j} VINPUT_{i.l,j} \tag{2}$$

where $VMCROP$ refers to the value of each crop (indexed by c). $VCROP$ denotes the value of cultivation activity's output, which equals to the total value of crops it produced. $VINPUT$ indicates the value of the cultivation activity's input, indexed by j (including both primary factors and intermediate inputs).

To ensure consistency, GTAP-SIMPLE-G requires that the sum of gridded input values equals the corresponding regional input values in GTAP database for both primary factors and intermediate inputs, as represented by the following equations:

$$\sum_{i}\sum_{l}\sum_{j} VINPUT_{i.l,j} = VOS_{cultivation} \tag{3}$$

$$VOS_{cultivation} = \sum_{m} VDFP_{m,cultivation} + \sum_{m} VMFP_{m,cultivation} + \sum_{k} EVFP_{k,cultivation} \tag{4}$$

where VOS indicates the value of an activity's output from the suppliers' side. $VDFP$ represents the value of domestic purchase of intermediate inputs by firms (producers), with m as the index for commodities. $VMFP$ refers to the value of imported purchases of intermediate inputs by firms, while $EVFP$ denotes the value of factors used by firms, with k as the index of factors. All variables in equation (4) (gridded inputs) and (5) (regional inputs) are measured at purchasers' prices. These equations indicate that the sum of cultivation input values at the grid cell level must equal the regional value of cultivation activity's inputs.

The model also specifies the requirement for cultivation output, represented as:

$$\sum_{i}\sum_{l} VMCROP_{i.l,c} = MAKES_{c,cultivation} \tag{5}$$

where $MAKES$ is the output of commodity production in the GTAP database, valued at producer's price.

To ensure that the gridded database preserves the spatial patterns from SIMPLE-G-Brazil and aligns with the regional value from GTAP for both cultivation output and inputs, it is necessary to conduct data balancing simultaneously along two dimensions with the RAS method, which has been applied widely in balancing input-output tables (Trinh and Phong, 2013). First, the gridded crop output value data processed in section 3.2 is taken as the initial matrix of output values (by grid cell and crops). Then the sum of inputs by grid cells (right hand of equation 4, disaggregated from GTAP's national input values to grid cell level using cost shares from SIMPLE-G database) and national sum of output by crops (right hand side of equation 5, from commodity value in GTAP) are calculated as the targeted row sum and column sum of this output value matrix.[11] Next, the output value matrix is updated iteratively, first with the ratio between the targeted row sum and current row sum, followed by the ratio between the targeted column sum and current column sum. This updating step continues until the sums of both rows and columns match their targeted values.[12] In each grid, the output value of each crop is further disaggregated to irrigated and rainfed with the initial share from the gridded crop output value data. Then the input value matrix (by inputs and irrigation types) is updated again with RAS, using the value by inputs for that grid cell as the targeted row sum and the sum of crop values by irrigation types in that grid cell as the targeted column sum. After the two-level RAS balancing step, the gridded data of outputs and inputs satisfies equations 2 through 5 across all dimensions simultaneously.

Another important step in connecting the gridded and regional databases is to account for irrigation inputs. Since the original GTAP database does not distinguish irrigation water and equipment from other inputs, the land input value in cultivation in the GTAP database is further disaggregated to break out the value of irrigation water which is assigned to the sector-specific natural resource input with the ratio between land and irrigation inputs summed from the adjusted gridded database. The natural resource input in cultivation represents the irrigation water and is supplied exogenously at the grid cell level. The irrigation equipment is treated as a part of capital inputs in GTAP-SIMPLE-G. So, its value is merged with capital inputs at the gridded level, guaranteeing the sum of gridded capital inputs matches the regional capital inputs from GTAP.

Once the major steps of data processing have been performed, the local level database is finalized with three additional steps: separating the cropland area by irrigation type (rainfed vs. irrigated), recalculating the quantities of crop

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[11] Since the GTAP database does not provide national value of irrigation water and equipment, the value of irrigation water and equipment were subtracted from the value of "land" and "capital" inputs respectively before the disaggregation.

[12] In this study, the criteria that one vector matches another vector is that their Euclidean distance is less than 10^{-6}.

production, and calculating the quantity of irrigation water. The gridded cropland area from MapBiomas was allocated to irrigation subsystems, using the ratio of irrigated and rainfed cropland area from SIMPLE-G-Brazil. Additionally, although the gridded crop quantities have been converted to values for aggregating SPAM2010 crops to GTAP categories (see section 3.2), it is also important to report changes in crop production quantities. Therefore, the quantity of each GTAP crop is recalculated using the price of the most representative crop within that category, as measured by value share.[13] In a similar manner, the quantity of gridded irrigation water is recalculated with the adjusted irrigation water value and irrigation water price (Cabral, 2023).

4. Calibration of parameters

Although most parameters used in GTAP-SIMPLE-G are available from either the GTAP model or from SIMPLE-G-Brazil, it is still necessary to obtain parameter values that govern land use conversion and multiple crop production at the local level, since these are new features in the integrated model. Among the new parameters introduced into GTAP-SIMPLE-G, the elasticities of transformation between cropland and pasture (ETCP) and between multiple crop types (ETMC) are particularly important.[14] The Nelder-Mead method, a derivative-free optimization algorithm capable of calibrating multiple parameters simultaneously (Singer and Nelder, 2009), is employed to calibrate ETCP and ETMC with historical data on land use and crop production at the state level (27 values).

The calibration of each elasticity of transformation using the Nelder-Mead method is an iterative process.[15] The first step is generating initial parameter values prior to iterations. To calibrate a parameter vector with N dimensions (here N = 27), N+1 parameter vector θ_i (i = 1, 2, …, N+1) are generated, each θ_i consists

[13] The quantity for each GTAP crop is recalculated with aggregated value of all crops belonging to this GTAP crop category, divided by the price of the single crop that takes the highest value share in that GTAP crop category (referred to as the "representative crop". The representative crop for each GTAP crop category and its value share (measured at 2017 baseline) in that crop are listed below: rice (rice, 100%), wheat (wheat, 100%), oilseeds (soybean, 98%), other grains (maize, 97%), sugar crops (sugar cane, 100%), vegetable & fruits (bananas, 14%), fibers (seed cotton (unginned), 97%) and other crops (coffee (green), 67%).

[14] Except for ETCP and ETMC, other parameters introduced in GTAP-SIMPLE-G are currently assigned a uniform value across all grid cells following GTAP-AEZ. For regional aggregation or allocation of the same commodity or factors, the elasticity of substitution is set as 1 and the elasticity of transformation is set as -1, while for the substitution or transformation elasticity between different factors, its value is set to be 0.5 or -0.5 respectively.

[15] The R scripts for calibration and post-simulation analysis are available at https://github.com/wangzhan90/GTAP-SIMPLE-G-Rcode.

of N elasticities randomly selected from a specified range. Although gridded data on the ranges of these parameters are not yet available, the GTAP-AEZ model sets the elasticity of transformation between cropland and pasture to be -0.5, while the elasticity of transformation among multiple crops within cropland is -1, for all regions and AEZs. Using the values from GTAP-AEZ as midpoints, the ranges of ETCP and ETMC are set to [-1. 0) and [-2. 0), respectively. Once the N+1 parameter vectors are randomly generated, each θ_i is applied to a subregional version of GTAP-SIMPLE-G, for which each grid cell represents a Brazilian state, to perform a hindcast from 2017 to 2012. [16] This hindcast process is driven by historical crop and livestock price changes from FAOSTAT, and also total land area changes from MapBiomas, to obtain the errors between simulated and historical data (described below). [17]

The second step in the Nelder-Mead method involves updating θ_i through iterations. In each iteration, the algorithm identifies the parameter vector with the highest error (denoted as θ_i^*) from the current set of θ_i, then updates θ_i^* using its reflection with respect to the centroid of other θ_i, assuming the reflection indicates a direction of reduced error. [18] The Nelder-Mead method may further expand or contract the reflection if doing so helps reduce the error or shrink all other θ_i to limit the searching space. Finally, the reflection replaces θ_i^*, and the next iteration begins. The algorithm terminates when the error falls below a specified tolerance or when the number of iterations reaches its maximum limit.

In this study, ETCP and ETMC are calibrated alternately, as they require distinct objective functions. Since ETCP governs land use allocation between cropland and pasture, its objective function is defined as the weighted sum of squared errors between simulated and observed land use area from MapBiomas for cropland and pasture, divided by the number of states:

$$\frac{1}{N}\left(w^{cropland}\sum_{s=1}^{N}\left(QCROPLAND_s^{sim} - QCROPLAND_s^{obs}\right)^2 + w^{pasture}\sum_{s=1}^{N}\left(QPLAND_s^{sim} - QPLAND_s^{obs}\right)^2\right) \tag{6}$$

[16] As the purpose here is to calibrate parameters at state level, this subregional version of GTAP-SIMPLE-G was created by aggregating all grid cells to the state that it belongs to. The version only contains 27 grid cells for Brazil (representing 26 states plus the federal district), which speeds up the iterative algorithm significantly.

[17] To mitigate short-term fluctuations in crop price, the data between 2012 and 2017 were used to fit a linear regression between price and year and the fitted value was used to calculate the price shock.

[18] If we consider each θ_i as one point in N-dimension space, then the reflection is the opposite point of θ_i^*, mirrored by the centroid of all other θ_i.

where $QCROPLAND$ and $QPLAND$ denote the area of cropland and pasture respectively, and s is the index of state. Considering the difference between the baseline areas of pasture and cropland, the sum of squared error for each land use category is adjusted with a weight (w) in the objective function. This weight is calculated as the square of the ratio between the national area of that land use category ($Q^{landuse}$) and the area of pasture:

$$w^{landuse} = (\frac{Q^{pasture}}{Q^{landuse}})^2 \quad (7)$$

Similarly, because ETMC governs the conversion from cultivation output to multiple crop commodities, its objective function is defined as the weighted sum of squared errors between simulated and observed crop output from the Brazilian Institute of Geography and Statistics (IBGE), also divided by the number of states.[19] In the calibration of ETMC, the error is calculated based on three major crop commodities: oilseeds (osd), sugar crops (c_b) and other grains (gro). These commodities represent significant proportions of the Brazilian crop value (osd: 35%; c_b: 15%; gro: 13%). Each commodity is dominated by a single crop (osd: soybean; c_b: sugar cane; gro: maize), which facilitate calibration with state-level, crop-specific historical data. The objective function is expressed as follows:

$$\frac{1}{N}(w^{osd}\sum_{s=1}^{N}\left(Qosd_s^{sim} - Qosd_s^{obs}\right)^2 + w^{gro}\sum_{i=1}^{N}\left(Qgro_s^{sim} - Qgro_s^{obs}\right)^2 + w^{c\_b}\sum_{i=1}^{N}(Qc\_b_s^{sim} - Qc\_b_s^{obs})^2) \quad (8)$$

where Qosd, Qgro and Qc_b represent the quantity of crop production for oilseeds, other grains, and sugar crops, respectively. To balance the crop commodities in the objective function, the sum of squared errors for each major crop is adjusted with a weight that equals the squared ratio between the crop price and the oilseeds price:

$$\mathrm{w}^{\mathrm{crop}} = (\frac{P^{crop}}{P^{osd}})^2 \quad (9)$$

The calibration is implemented in R (version 4.2.0). For each elasticity, the maximum number of iterations is set to 40. Initially, ETCP is calibrated using an

[19] To avoid the difference between crop output data from IBGE and the baseline data balanced with GTAP, the 2012 data for calibration were calculated with the percentage change of crop output between 2017 and 2012 from IBGE applied to the baseline data.

initial guess of ETMC, followed by calibrating ETMC with the previously calibrated ETCP. [20] This iterative process continues until the parameter values after calibration converge. Finally, the calibrated ETCP and ETMC are applied in another hindcast back to 2012, and the simulated land use and crop production are compared with observed data at the state level. As to the land use pattern (Figure 4), the state-level simulation results align closely with the historical data, indicating the model, data and parameters effectively capture land use conversion in response to economic shocks.

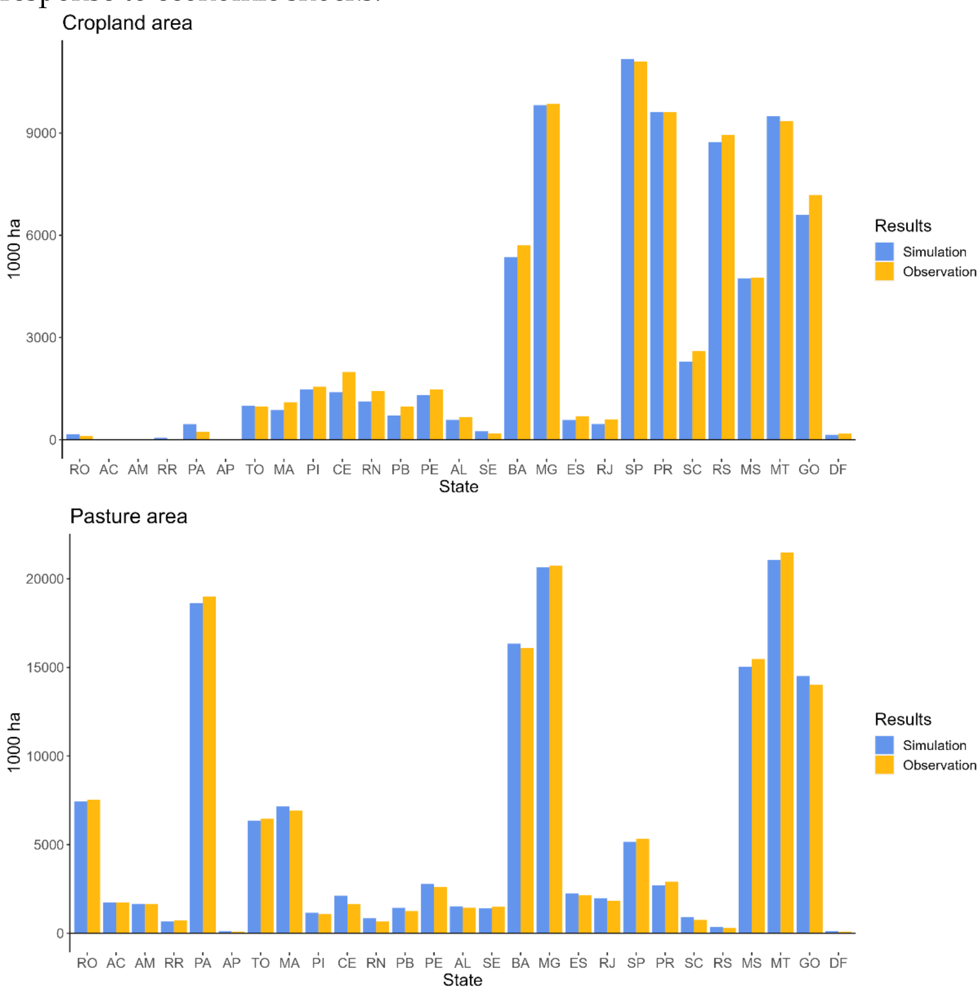


Figure 4. Simulated and observed land use area in 2012**.**

Source: Author illustration.

[20] The initial guess of ETMC is -1.25 for irrigated cultivation and -0.75 for rainfed cultivation, given that the conversion between crops is less elastic for rainfed cultivation.

Regarding crop output (Figure 5), the simulation results generally align with the state level pattern of observed data, especially for sugar crops. However, inconsistencies remain in the output of oilseeds and other grains in several states, such as Paraná (PR), Rio Grande do Sul (RS), Mato Grosso (MT) and Minas Gerais (MG). These inconsistencies are primarily due to the objective function used for calibrating ETMC. Since the quantity of sugar crops significantly exceeds that of oilseeds and other grains, even with adjustments of price ratios, the error associated with sugar crops still dominates the objective function. As a result, the calibrated ETMC prioritizes minimizing errors in sugar crops, causing less consistent results for other crop categories. This issue could be addressed by extending the multi-cropping system in GTAP-SIMPLE-G, a potential future direction discussed in section 6.

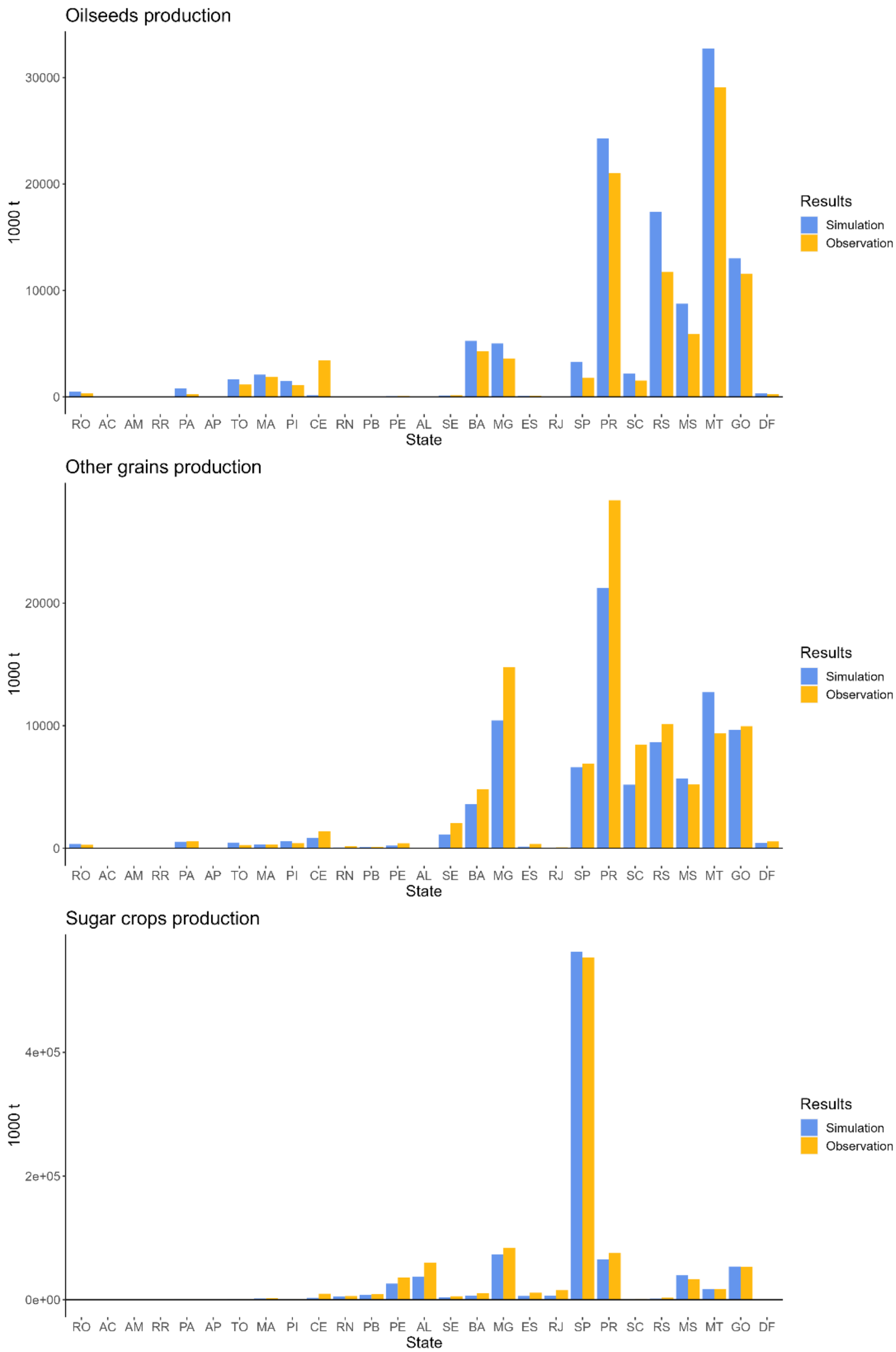


Figure 5. Simulated and observed major crop output in 2012**.**

Source: Author illustration.

5. An illustrative analysis: US-China soybean trade and its impacts on Brazilian land use and crop production at the local level

The key strength of GTAP-SIMPLE-G is enabling the GLG linkages, which captures interactions between global and local level economic systems and the spillover effects on both levels. Taking the US–China soybean trade as an example, when China imposed retaliatory tariffs on US-produced soybeans (Li et al., 2019), it not only reduced the demand for soybeans from the US, but also stimulated soybean imports from Brazil. However, the impact of China's soybean demand from Brazil is not uniform: it results in spatially heterogeneous effects on crop production and land use conversions. Through its GLG framework, GTAP-SIMPLE-G provides researchers a capable tool to examine how global soybean trade influences Brazilian agriculture and land use through spillover effects across countries and within Brazil, as well as across commodities and activities.

For illustrative purposes, a simplified scenario was applied in the simulation: a 25% increase in the power of import tariff on oilseeds from the US to China. Although Brazil was not directly targeted by the tariff, this shock increases the demand for Brazilian soybean exports, stimulating soybean production and making it more competitive against other crops. Also, it makes crop production more attractive thereby resulting in land use competition. It is important to note that, besides this tariff, other drivers influenced global soybean trade flow during the historical US-China trade dispute. These drivers included the outbreak of swine fever, which reduced China's soybean demand (Ma et al., 2024); and the US subsidy to producers to mitigate the tariffs impacts on domestic soybean producers (Adjemian et al., 2021). The purpose of this analysis is not to replicate historical observations after the tariff but to demonstrate the GLG framework in GTAP-SIMPLE-G that connects global trade shock and local production and land use responses.

Table 2 presents the simulation results showing percentage changes in commodity production from cultivation, livestock and forestry activities for the US, Brazil, and China. When China imposes the aforementioned increase in tariff on US soybean exports, the US oilseeds output contracts by 9.29%. The decline in soybean demand induces farmers to shift production towards other crops, resulting in an increase in output for all non-soybean crops, except sugar crops. This shift also leads landowners and ranchers to allocate more land for grazing rather than cultivation, causing a net increase in cattle production. In contrast, China's tariff on US soybean imports boosts the demand for Brazilian soy. This creates a challenge for meeting its domestic soybean demand. This results in a 5.45% increase in China's domestic soybean production to reduce external dependency, alongside a higher demand for non-US soybean. As a result, Brazil's oilseeds production expands by 2.82%, while the output of nearly all non-soybean crops, except wheat and plant-based fibers, decline. Among the three major crop categories - oilseeds, sugar crops and other grains - sugar crops experience the highest reduction in output by 1.57%. Furthermore, the increased demand for soybean exports also makes cropland more profitable, leading to a shift in land use away from grazing and forestry, and reducing outputs in these activities. In terms of level changes, the tariff results in a 3.93 million metric ton increase in Brazil's oilseeds production, a 15.30 million metric ton reduction in sugar crops output, and a 0.08 million metric ton decline in in other grains production. Additional results on national and state level in Brazil and national level in other global regions except US, Brazil and China are available in Appendix E (Table E.1 and E.2, respectively).

Table 2. Percentage changes (%) in national output of commodities.

Commodity	USA	Brazil	China
Rice	0.51	-0.32	-0.01
Wheat	0.65	0.56	-0.07
Other grains	0.14	-0.07	-0.05
Vegetable & fruits	0.41	-0.49	-0.02
Oilseeds	-9.29	2.82	5.45
Sugar crops	-0.35	-1.57	-0.02
Plant-based fibers	0.28	0.65	0.06
Other crops	0.78	-2.25	0.07
Cattle	0.37	-0.28	-0.02
Forestry	-0.66	-0.68	0.03

Source: Author calculation

Table 2 presents the national level impacts in the typical GTAP manner. However, the local level effects are potentially more important for accessing tariff impacts and facilitating planning at the state and local levels. Figure 6 illustrates the gridded output changes for the three major crops - soybean, sugar cane and maize – represented by oilseeds, sugar crops and other grains, respectively. The increased demand for soybean exports leads to a nationwide rise in soybean production, concentrated in the major soybean producing states of Center-West and South Brazil. As soybean production becomes more profitable, it draws agricultural inputs away from other crops and from other regions within Brazil. As a result, sugar cane production, primarily concentrated in São Paulo state in Southeast Brazil, experiences the largest reduction in output (Figure 6B). Interestingly, maize production displays notable spatial heterogeneity (Figure 6C): maize output rises in Center-West states such as Mato Grosso, Goiás and Mato Grosso do Sul, while declining in other states. This finding highlights the importance of multi-cropping at the local level. In Brazil, producers in Mato Grosso, Goiás and Mato Grosso do Sul are key suppliers of second-season maize, accounting for 45%, 14% and 12% of the national total, respectively. This crop follows on the heels of soy production and therefore benefits from increased soybean cultivation. In contrast, first-season maize crops are primarily cultivated in South and Southeast Brazil (Foreign Agricultural Service, USDA, 2024). This expansion in soybeans directly competes with first-season maize for cropland, causing its output to decline. Conversely, second-season maize does not compete with soybean on cropland but benefits from soybean expansion as it attracts additional cultivation inputs from rest of Brazil, as shown the simulation results.

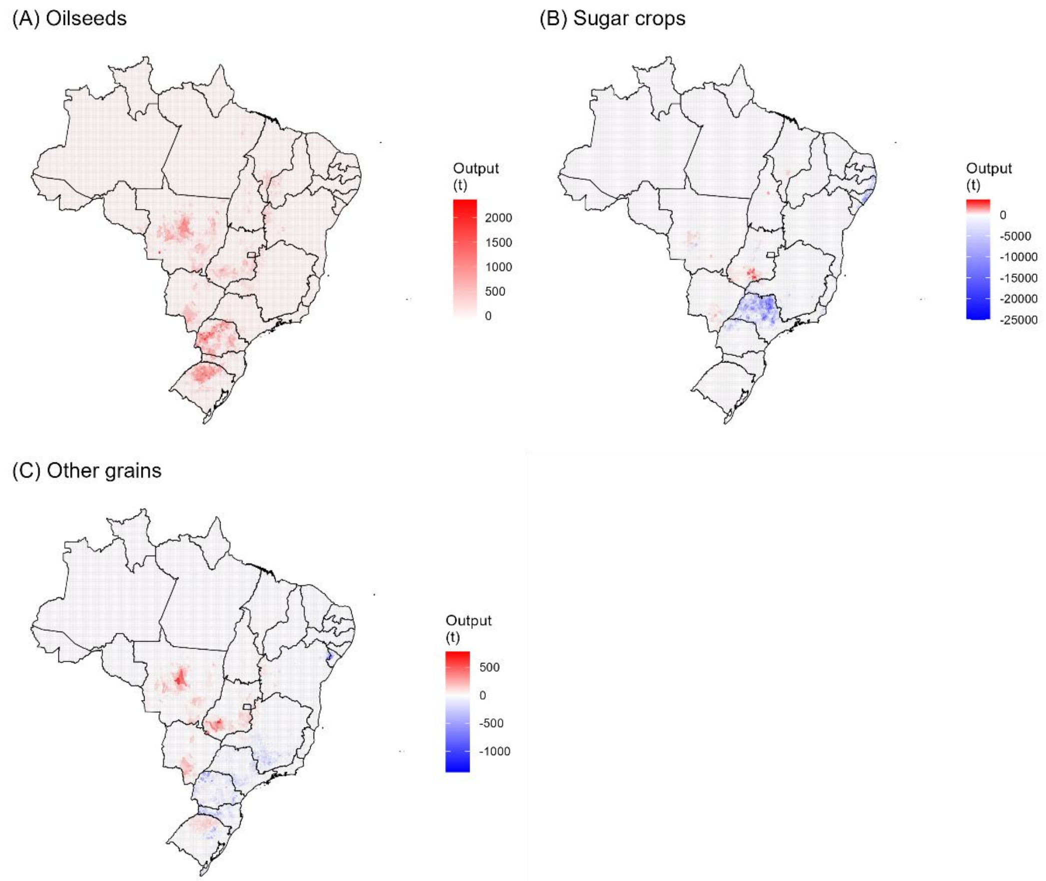


Figure 6. Change of gridded crop output compared with baseline.

Source: Author illustration.

In addition to crop production, GTAP-SIMPLE-G simulates the tariff impacts on land use in Brazil. Nationally, the tariff increase imposed by China on the US results in a 0.18 million ha expansion (percentage change: +0.20%) in cropland, along with a 0.16 million ha reduction (-0.10%) in pasture area and a 0.02 million ha decrease (-0.21%) in forest plantation in Brazil. At the gridded level, Figure 7A shows that cropland expansion aligns closely with the soybean expansion pattern (Figure 6A), indicating that increased land demand for soybean production is the key driver of land use change. In response to soybean expansion, Brazil would experience not only a conversion from pasture to cropland but also a shift in pasture pattern towards its eastern regions (Figure 7B). Finally, the simulation shows a reduction in forest plantation area, though less severe than the decrease in pasture, concentrating primarily in South Brazil (Figure 7C). In summary, this illustrative analysis demonstrates that the GLG framework enables researchers to capture the heterogeneity in baseline data and responses to shocks, along with local-specific mechanisms such as the spillover effects and multi-cropping. The GLG feature enhances the understanding of the economic system and allows for a more comprehensive assessment of policies.

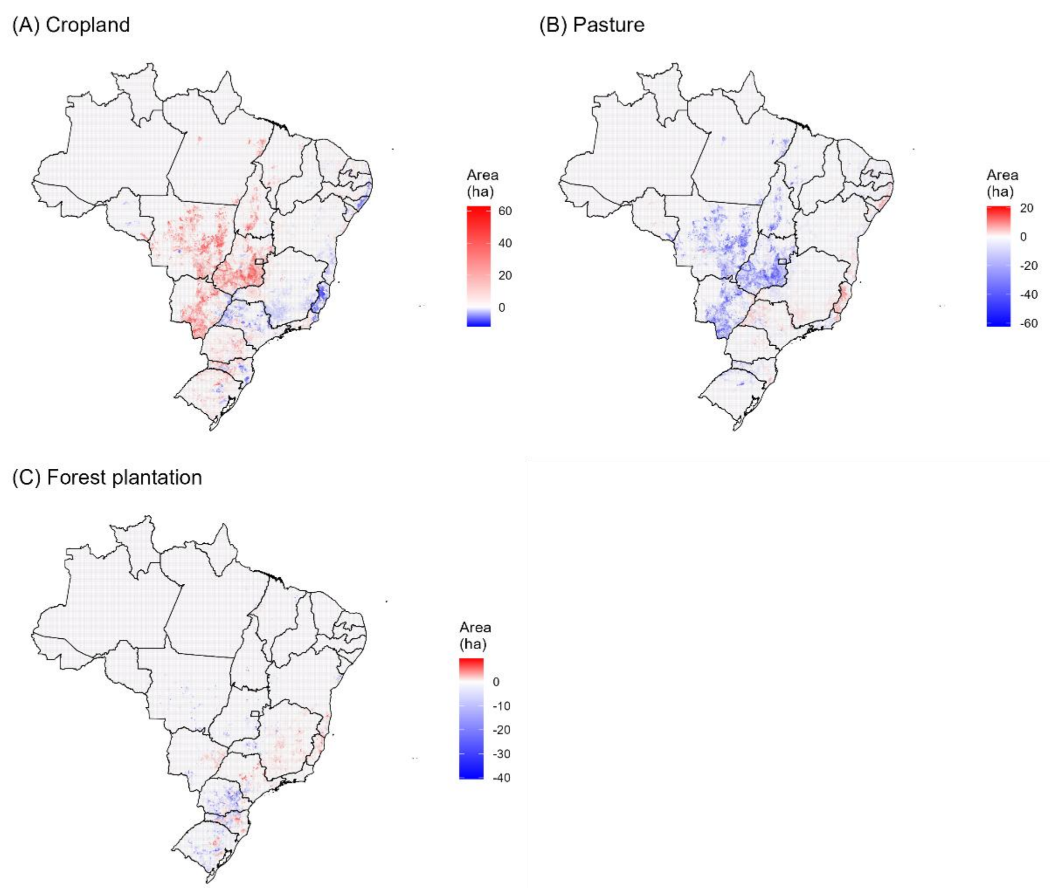


Figure 7. Change of gridded land use area compared with baseline 2017.

Source: Author illustration.

6. Discussion

The integration of GLG linkages within economic modelling has been explored for decades but still remains limited by several gaps: an intradisciplinary focus, under-addressed Local-to-Global linkages, and challenges in subnational parameter estimation and calibration (Hertel et al., 2019). GTAP-SIMPLE-G contributes to the GLG literature by connecting the PE structure of gridded land use and crop production with the GE supply chain structure encompassing production, consumption and bilateral trade in all commodities and services. This connection expands research from land use and agriculture to broader economic systems. Additionally, the GTAP-SIMPLE-G framework introduced in this paper facilitates interdisciplinary studies with researchers in ecology, hydrology, and climate science fields. These researchers typically focus on subregional or grid cell level of natural systems, which are not yet addressed in national level economic models.

GTAP-SIMPLE-G strengthens GLG integration by enhancing Local-to-Global linkages. Instead of simulating global responses and then disaggregating them to the local level, GTAP-SIMPLE-G models land use allocation and crop production with local level producers, whose outputs are aggregated to represent national production for focus regions. A key advantage of this framework is its capacity to simulate the impact of local level shocks such as conservation policies (Pacheco et al., 2018; Y. Qin et al., 2023) and infrastructure expansions (Wang et al., 2024; Costa et al., 2022), thereby accessing their impacts both within specific locations and across the country through market linkages. These impacts can also influence other global regions through trade flows.

Another key contribution of this study lies in parameter calibration. Typically, parameter calibration involves converting a structural model to reduced-form regressions and estimating parameters empirically. However, this method is often infeasible for more complex models. As a result, even models with local level components may use uniform parameter values. This study addresses this issue by introducing the derivative-free Nelder-Mead method to simultaneously calibrate elasticities of transformation on land use and multi-crop production at state level with observed data. This approach can be generalized to other regions in future studies, to better represent the spatial heterogeneity not only on data but also parameters.

In addition to contributions on model structure and parameter calibration, this paper revisits the impacts of China's tariff on US soybean export on Brazil. At the national level, this study's findings align with existing research (Carvalho et al.,2019; Dhoubhadel et al., 2023), while the grid cell simulation results provide deeper insights into the location-specific mechanisms, such as the competition between soybean and other crops and the pasture – cropland conversion. Especially, this model extends the multi-production system of the standard GTAP framework to the local level. As interest in the soybean – maize multi-cropping system continues to grow (Bigolin and Talamini, 2024; Gurgel et al., 2024; Moreira et al., 2020), GTAP-SIMPLE-G is expected to further contribute to multi-cropping research by linking this system to a broader set of economic components and external drivers.

Several limitations still exist and should be addressed as future directions for improvements. First, validation after calibration still displays inconsistency in soybean and maize production for several states. One potential solution is to create a separate layer for the soybean-maize multi-cropping system and calibrate an additional elasticity of transformation between these two crops. Second, GTAP-SIMPLE-G simulation results should be interpreted with caution, as they represent changes between two equilibrium states before and after external shocks. In practice, the economy may not be sufficiently responsive to external shocks in the short term, necessitating a different set of parameters (Haqiqi, Grogan, et al., 2023) or model modifications to limit the mobility for intermediate inputs, labor, and capital.

Third, GTAP-SIMPLE-G models forest plantation with an endogenous land use allocation system following GTAP-AEZ. However, natural forest is excluded from this system because the land value of natural forest – especially its non-market ecosystem services – has not been represented with monetary term in this model. As a result, commercial encroachment into the natural forest should be estimated separately and applied to the model exogenously. To simulate natural forests' responses to economic drivers endogenously, GTAP-SIMPLE-G could be extended by incorporating the non-market value of natural forests' ecosystem services into the regional household's utility function, as performed in the FABLE model (Steinbuks et al., 2024). Alternatively, researchers can model land supply using access cost to natural forests (Gouel and Hertel, 2006; Gurgel et al., 2021) or with the combination of a long-run supply curve of total agricultural lands and CET-based land allocation systems between cropland and forest (Woltjer et al., 2014).

Fourth, GTAP-SIMPLE-G employs the QCET and QCES functions to preserve the consistency in quantities for land use and crop output between gridded and regional levels, but their presence causes inconsistencies in the welfare evaluation module inherited from the GTAP model. In view of that, an alternative version of GTAP-SIMPLE-G is also provided in the supplementary materials, which replaces QCET and QCES functions with CET and CES functions, respectively. This alternative version could be applied when researchers are more interested in welfare impacts.

As with the standard GTAP model, GTAP-SIMPLE-G also serves as a platform for future extensions of GLG analysis. While this manuscript focuses on the gridded land use and cultivation systems in Brazil, the framework of GTAP-SIMPLE-G can be readily generalized to any number of gridded regions at any specified resolutions. Theoretically, it is possible to apply the GTAP-SIMPLE-G framework to integrate GTAP with the global version of SIMPLE-G model, representing global crop production across 1.3 million grid cells (Haqiqi, Grogan, et al., 2023). However, such integration is not only extremely time-consuming in database development, parameter calibration, model validation, and experiment simulation, but also unnecessary for many research questions. The flexibility of the GTAP-SIMPLE-G framework leaves the option for readers to further modify this model to any desired spatial resolutions for various research questions. With the spatial distribution of livestock (Gilbert et al., 2018), it is also possible to extend the livestock production sector at the gridded level, capturing the heterogeneity in pasture as well.

Since GTAP-SIMPLE-G connects external shocks with gridded land use, a natural extension would be to map land use change with environmental indicators such as carbon storage, wildlife habitat, and ecosystem services to assess these shocks' environmental impacts. Finally, while this study focuses on interactions between cultivation, livestock, and forestry sectors, GTAP-SIMPLE-G also enables exploration of industrial-agricultural linkages, for example energy supply shocks' impacts on soybean, corn, and sugar cane for biofuel demand and the associated carbon emissions. Expanding research scope across industrial and agricultural sectors could provide a more comprehensive understanding of food-energy-environment nexus.

7. Conclusion

This paper introduces GTAP-SIMPLE-G, a recent advancement in integrating GLG linkages into CGE modeling. GTAP-SIMPLE-G connects GE-based national demand, supply and bilateral trade flows with PE-based gridded land use and crop production. This model captures several location-specific economic mechanisms that are not possible at the national level, such as spatial input mobility, spillover effects, and heterogenous multi-cropping systems. Taking Brazil as an example, this paper provides detailed guidelines for processing raw data, creating a gridded database, and simultaneously calibrating multiple parameters at the subnational level. Those guidelines not only benefit studies focused on Brazil but also support broader applications of GTAP-SIMPLE-G in other regions.

This paper further demonstrates GTAP-SIMPLE-G's capacity to perform GLG analysis, using the example of China's tariff on US soybean exports and its impacts on Brazilian agriculture and land use. This model captures threefold spillover effects across countries, regions within Brazil and sectors. Simulation results show that China shifts to Brazilian soybean exports following the tariff change, boosting soybean production and reducing output of other crops. At the local level, soybean expansion reduces sugar cane production in the Southeast region, due to the competition for cultivation inputs between both crops and regions. Meanwhile, maize production rises in the Center-West region because of the multi-cropping between soybean and second-season maize but declines in regions where soybean expansion competes with first-season maize. Finally, the tariff leads to land use conversion from pasture to cropland and reduces cattle production. These findings highlight the importance of the GLG framework in economic modeling, as it uncovers local economic mechanisms that remain obscured in national economic models but are still critical for policy makers and agricultural stakeholders. In summary, the combined GTAP-SIMPLE-G model has demonstrated its capacity to contribute to future studies and policy assessments where Global-to-Local-to-Global linkages are important.

Acknowledgements

This study is supported by NSF projects "INFEWS/T2: Identifying Sustainability Solutions through Global-Local-Global Analysis of a Coupled Water-Agriculture-Bioenergy System" (CBET-1855937), "AccelNet: GLASSNET: Networking Global to Local Analyses to Inform Sustainable Investments in Land and Water Resources" (OISE-2020635), and "HDR Institute: Geospatial Understanding through an Integrative Discovery Environment" (OAC-2118329). I thank anonymous reviewers for their valuable and constructive comments on this manuscript.

References

Adjemian, M.K., A. Smith, and W. He. 2021. "Estimating the Market Effect of a Trade War: The Case of Soybean Tariffs." *Food Policy,* 105 (December):102152. https://doi.org/10.1016/j.foodpol.2021.102152.

Aguiar, A., M. Chepeliev, E. Corong, and D. van der Mensbrugghe. 2022. "The Global Trade Analysis Project (GTAP) Data Base: Version 11." *Journal of Global Economic Analysis,* 7(2). https://doi.org/10.21642/JGEA.070201AF.

Baldos, U.L.C., I. Haqiqi, T.W. Hertel, M. Horridge, and J. Liu. 2020. "SIMPLE-G: A Multiscale Framework for Integration of Economic and Biophysical Determinants of Sustainability." *Environmental Modelling & Software*,133 (November):104805. https://doi.org/10.1016/j.envsoft.2020.104805.

Berndt, E.R., and L.R. Christensen. 1973. "The Internal Structure of Functional Relationships: Separability, Substitution, and Aggregation." *The Review of Economic Studies,* 40(3): 403. https://doi.org/10.2307/2296459.

Bigolin, T., and E. Talamini. 2024. "Impacts of Climate Change Scenarios on the Corn and Soybean Double-Cropping System in Brazil." *Climate,* 12(3): 42. https://doi.org/10.3390/cli12030042.

Cabral, U. 2023. "In 2020, Brazil Consumes 6.2 Liters of Water for Each R$1 Generated by the Economy." Agência de Notícias. 2023. https://agenciadenoticias.ibge.gov.br/en/agencia-news/2184-news-agency/news/37059-em-2020-para-cada-r-1-00-gerado-pela-economia-foram-consumidos-6-2-litros-de-agua-2#.

Carvalho, M., A. Azevedo, and A. Massuquetti. 2019. "Emerging Countries and the Effects of the Trade War between US and China." *Economies*,7(2): 45. https://doi.org/10.3390/economies7020045.

Chepeliev, M. 2020. "The GTAP 10A Data Base with Agricultural Production Targeting Based on the Food and Agricultural Organization (FAO) Data." GTAP Research Memoranda Series. GTAP Research Memoranda Series. GTAP Research Memoranda. https://doi.org/10.21642/GTAP.RM35.

Colussi, J., N. Paulson, G. Schnitkey, and C. Zulauf. 2024. "Comparing Corn Production Direct Costs: United States vs. Brazil." *Farmdoc Daily,* 14(1). https://farmdocdaily.illinois.edu/2024/01/comparing-corn-production-direct-costs-united-states-vs-brazil.html.

Colussi, J., G. Schnitkey, J. Janzen, and N. Paulson. 2024. "The United States, Brazil, and China Soybean Triangle: A 20-Year Analysis." *Farmdoc Daily*, no. 14, 35.

Corong, E.L., T.W. Hertel, R. McDougall, M.E. Tsigas, and D. van der Mensbrugghe. 2017. "The Standard GTAP Model, Version 7." *Journal of Global Economic Analysis,* 2(1): 1–119. https://doi.org/10.21642/JGEA.020101AF.

Costa, W., B. Soares-Filho, and R. Nobrega. 2022. "Can the Brazilian National Logistics Plan Induce Port Competitiveness by Reshaping the Port Service Areas?" *Sustainability,* 14(21): 14567. https://doi.org/10.3390/su142114567.

Dhoubhadel, S.P., W. Ridley, and S. Devadoss. 2023. "Brazilian Soybean Expansion, US–China Trade War, and US Soybean Exports." *Journal of the Agricultural and Applied Economics Association,* 2(3): 446–60. https://doi.org/10.1002/jaa2.71.

Dou, Y., R.F.B. da Silva, H. Yang, and J. Liu. 2018. "Spillover Effect Offsets the Conservation Effort in the Amazon." *Journal of Geographical Sciences,* 28(11): 1715–32. https://doi.org/10.1007/s11442-018-1539-0.

Food and Agriculture Organization of the United Nations. 2023. "FAOSTAT." FAOSTAT. https://www.fao.org/faostat/en/#home.

Foreign Agricultural Service, USDA. 2024. "Brazil Production." Country Summary. 2024. https://ipad.fas.usda.gov/countrysummary/default.aspx?id=BR.

Friedl, M., and D. Sulla-Menashe. 2019. "MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data Set]." NASA EOSDIS Land Processes DAAC. 2019. https://doi.org/10.5067/MODIS/MCD12Q1.006.

Gilbert, M., G. Nicolas, G. Cinardi, T.P. Van Boeckel, S.O. Vanwambeke, G.R. William Wint, and T.P. Robinson. 2018. "Global Distribution Data for Cattle, Buffaloes, Horses, Sheep, Goats, Pigs, Chickens and Ducks in 2010." *Scientific Data,* 5(1): 180227. https://doi.org/10.1038/sdata.2018.227.

Gouel, C., and T. Hertel. 2006. "Introducing Forest Access Cost Functions into a General Equilibrium Model." GTAP Research Memoranda Series. GTAP Research Memoranda Series. GTAP Research Memoranda. https://doi.org/10.21642/GTAP.RM08.

Grogan, D., S. Frolking, D. Wisser, A. Prusevich, and S. Glidden. 2022. "Global Gridded Crop Harvested Area, Production, Yield, and Monthly Physical Area Data circa 2015." *Scientific Data,* 9(1): 15. https://doi.org/10.1038/s41597-021-01115-2.

Gurgel, A.C., J. Reilly, and E. Blanc. 2021. "Agriculture and Forest Land Use Change in the Continental United States: Are There Tipping Points?" *iScience,* 24(7): 102772. https://doi.org/10.1016/j.isci.2021.102772.

Gurgel, A.C., J.E.A. Seabra, S.M. Arantes, M.M.R. Moreira, L.R. Lynd, and R. Galindo. 2024. "Contribution of Double-Cropped Maize Ethanol in Brazil to Sustainable Development." *Nature Sustainability,* 7(11): 1429–40. https://doi.org/10.1038/s41893-024-01424-5.

Haqiqi, I., L. Bowling, S. Jame, U. Baldos, J. Liu, and T. Hertel. 2023. "Global Drivers of Local Water Stresses and Global Responses to Local Water Policies in the United States." *Environmental Research Letters,* 18(6): 065007. https://doi.org/10.1088/1748-9326/acd269.

Haqiqi, I., D.S. Grogan, M.B. Horeh, J. Liu, U.L.C. Baldos, R. Lammers, and T.W. Hertel. 2023. "Local, Regional, and Global Adaptations to a Compound Pandemic-Weather Stress Event." *Environmental Research Letters*, 18(3): 035005. https://doi.org/10.1088/1748-9326/acbbe3.

Haqiqi, I., and T.W. Hertel. 2024. *SIMPLE-G: A Gridded Economic Approach to Sustainability Analysis of the Earth's Land and Water Resources*. Springer. https://doi.org/10.1007/978-3-031-68054-0.

Havlík, P., H. Valin, A. Mosnier, M. Obersteiner, J.S. Baker, M. Herrero, M.C. Rufino, and E. Schmid. 2013. "Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions." *American Journal of Agricultural Economics*, 95(2): 442–48. https://doi.org/10.1093/ajae/aas085.

Hertel, T. 2000. "Applied General Equilibrium Analysis of Agricultural and Resource Policies." GTAP Working Paper. GTAP Working Paper. GTAP Working Paper. https://doi.org/10.21642/GTAP.WP03.

Hertel, T., H.-L. Lee, S. Rose, and B. Sohngen. 2008. "Modeling Land-Use Related Greenhouse Gas Sources and Sinks and Their Mitigation Potential." GTAP Working Paper. GTAP Working Paper. GTAP Working Paper. https://doi.org/10.21642/GTAP.WP44.

Hertel, T.W. 1997. *Global Trade Analysis: Modeling and Applications*. Cambridge University Press.

Hertel, T.W., U.L.C. Baldos, and D. van der Mensbrugghe. 2016. "Predicting Long-Term Food Demand, Cropland Use, and Prices." *Annual Review of Resource Economics,* 8(1): 417–41. https://doi.org/10.1146/annurev-resource-100815-095333.

Hertel, T.W., A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin, and D.M. Kammen. 2010. "Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-Mediated Responses." *BioScience,* 60(3): 223–31. https://doi.org/10.1525/bio.2010.60.3.8.

Hertel, T.W., E. Irwin, S. Polasky, and N. Ramankutty. 2023. "Focus on Global–Local–Global Analysis of Sustainability." *Environmental Research Letters,* 18(10): 100201. https://doi.org/10.1088/1748-9326/acf8da.

Hertel, T.W., T.A.P. West, J. Börner, and N.B. Villoria. 2019. "A Review of Global-Local-Global Linkages in Economic Land-Use/Cover Change Models." *Environmental Research Letters*, 14(5): 053003. https://doi.org/10.1088/1748-9326/ab0d33.

Hofste, R. 2019. "FAOSTAT_crops_items." Github. 2019. https://github.com/wri/MAPSPAM/blob/master/FAO/FAOSTAT_crops_items.csv.

Horridge, J.M., M. Jerie, D. Mustakinov, and F. Schiffmann. 2018. *GEMPACK Manual*. Victoria University, Centre of Policy Studies/IMPACT Centre.

Horridge, M. 2019. "Using CRETH to Make Quantities Add up without Efficiency Bias." In. Warsaw. https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5775.

International Food Policy Research Institute. 2024. "Global Spatially-Disaggregated Crop Production Statistics Data for 2020 Version 1.0.0." Harvard Dataverse. https://doi.org/10.7910/DVN/SWPENT.

Itakura, K. 2020. "Evaluating the Impact of the US–China Trade War." *Asian Economic Policy Review,* 15(1): 77–93. https://doi.org/10.1111/aepr.12286.

Johnson, J.A., U.L. Baldos, E. Corong, T. Hertel, S. Polasky, R. Cervigni, T. Roxburgh, G. Ruta, C. Salemi, and S. Thakrar. 2023. "Investing in Nature Can Improve Equity and Economic Returns." *Proceedings of the National Academy of Sciences,* 120(27): e2220401120. https://doi.org/10.1073/pnas.2220401120.

Johnson, J.A., M.E. Brown, E. Corong, J.P. Dietrich, R.C. Henry, P.J. Von Jeetze, D. Leclère, A. Popp, S.K. Thakrar, and D.R. Williams. 2023. "The Meso Scale as a Frontier in Interdisciplinary Modeling of Sustainability from Local to Global Scales." *Environmental Research Letters,* 18(2): 025007. https://doi.org/10.1088/1748-9326/acb503.

Kim, K.-H., Y. Doi, N. Ramankutty, and T. Iizumi. 2021. "A Review of Global Gridded Cropping System Data Products." *Environmental Research Letters,* 16(9): 093005. https://doi.org/10.1088/1748-9326/ac20f4.

Li, M., E. Balistreri, and W. Zhang. 2019. "The US-China Trade War: Tariff Data and General Equilibrium Analysis." Center for Agricultural and Rural Development (CARD) at Iowa State University.

Lima, C.Z.de. 2017. "Impacts of Low Carbon Agriculture in Brazil: A CGE Application." PhD Thesis, Viçosa, Brazil: Universidade Federal de Viçosa.

Lotze-Campen, H., C. Müller, A. Bondeau, S. Rost, A. Popp, and W. Lucht. 2008. "Global Food Demand, Productivity Growth, and the Scarcity of Land and Water Resources: A Spatially Explicit Mathematical Programming Approach." *Agricultural Economics,* 39(3): 325–38. https://doi.org/10.1111/j.1574-0862.2008.00336.x.

Ma, M., M.S. Delgado, and H.H. Wang. 2024. "Risk, Arbitrage, and Spatial Price Relationships: Insights from China's Hog Market under the African Swine Fever." *Journal of Development Economics,* 166 (January):103200. https://doi.org/10.1016/j.jdeveco.2023.103200.

MapBiomas Project. 2023. "Collection 8 of the Annual Land Cover and Land Use Maps of Brazil (1985-2022)." https://doi.org/10.58053/MapBiomas/VJIJCL.

Metzger, J.P., M.M.C. Bustamante, J. Ferreira, G.W. Fernandes, F. Librán-Embid, V.D. Pillar, P.R. Prist, R.R. Rodrigues, I.C.G. Vieira, and G.E. Overbeck. 2019. "Why Brazil Needs Its Legal Reserves." *Perspectives in Ecology and Conservation,* 17(3): 91–103. https://doi.org/10.1016/j.pecon.2019.07.002.

Moreira, M.M.R., J.E.A. Seabra, L.R. Lynd, S.M. Arantes, M.P. Cunha, and J.J.M. Guilhoto. 2020. "Socio-Environmental and Land-Use Impacts of Double-Cropped Maize Ethanol in Brazil." *Nature Sustainability,* 3(3): 209–16. https://doi.org/10.1038/s41893-019-0456-2.

Pacheco, A.A., A.C.O. Neves, and G.W. Fernandes. 2018. "Uneven Conservation Efforts Compromise Brazil to Meet the Target 11 of Convention on Biological Diversity." *Perspectives in Ecology and Conservation,* 16(1): 43–48. https://doi.org/10.1016/j.pecon.2017.12.001.

Qin, X., B. Wu, H. Zeng, M. Zhang, and F. Tian. 2023. "GGCP10: A Global Gridded Crop Production Dataset at 10km Resolution from 2010 to 2020." Harvard Dataverse. https://doi.org/10.7910/DVN/G1HBNK.

Qin, Y., X. Xiao, F. Liu, F.De.Sa.E. Silva, Y. Shimabukuro, E. Arai, and P. Martin Fearnside. 2023. "Forest Conservation in Indigenous Territories and Protected Areas in the Brazilian Amazon." *Nature Sustainability,* 6(3): 295–305. https://doi.org/10.1038/s41893-022-01018-z.

Ray, S., I. Haqiqi, A.E. Hill, J.E. Taylor, and T.W. Hertel. 2023. "Labor Markets: A Critical Link between Global-Local Shocks and Their Impact on Agriculture." *Environmental Research Letters,* 18(3): 035007. https://doi.org/10.1088/1748-9326/acb1c9.

Singer, S., and J. Nelder. 2009. "Nelder-Mead Algorithm." *Scholarpedia* 4 (7): 2928. https://doi.org/10.4249/scholarpedia.2928.

Steinbuks, J., Y. Cai, J. Jaegermeyr, and T.W. Hertel. 2024. "Assessing Effects of Climate and Technology Uncertainties in Large Natural Resource Allocation Problems." *Geoscientific Model Development,* 17(12): 4791–4819. https://doi.org/10.5194/gmd-17-4791-2024.

Stevenson, J.R., N.Villoria, D. Byerlee, T. Kelley, and M. Maredia. 2013. "Green Revolution Research Saved an Estimated 18 to 27 Million Hectares from Being Brought into Agricultural Production." *Proceedings of the National Academy of Sciences,* 110(21): 8363–68. https://doi.org/10.1073/pnas.1208065110.

Taheripour, F., T.W. Hertel, and N. Ramankutty. 2019. "Market-Mediated Responses Confound Policies to Limit Deforestation from Oil Palm Expansion in Malaysia and Indonesia." *Proceedings of the National Academy of Sciences,* 116(38): 19193–99. https://doi.org/10.1073/pnas.1903476116.

Tang, F.H.M., T.H. Nguyen, G. Conchedda, L. Casse, F.N. Tubiello, and F. Maggi. 2024. "CROPGRIDS: A Global Geo-Referenced Dataset of 173 Crops." *Scientific Data,* 11(1): 413.https://doi.org/10.1038/s41597-024-03247-7.

Thenkabail, P.S., P.G. Teluguntla, J. Xiong, A. Oliphant, R.G. Congalton, M. Ozdogan, M.K. Gumma, J.C. Tilton, C. Giri, and C. Milesi. 2021. "Global Cropland-Extent Product at 30-m Resolution (GCEP30) Derived from Landsat Satellite Time-Series Data for the Year 2015 Using Multiple Machine-Learning Algorithms on Google Earth Engine Cloud." 2330–7102. US Geological Survey.

Torres, S., E. Moran, and R. Silva. 2017. "Property Rights and the Soybean Revolution: Shaping How China and Brazil Are Telecoupled." *Sustainability,* 9(6): 954. https://doi.org/10.3390/su9060954.

Trinh, B., and N.V. Phong. 2013. "A Short Note on RAS Method." *Advances in Management & Applied Economics,* 3(4): 133–37.

Van Der Mensbrugghe, D., and J.C. Peters. 2020. "Volume Preserving CES and CET Formulations." GTAP Working Paper. GTAP Working Paper. GTAP Working Paper. https://doi.org/10.21642/GTAP.WP87.

Villoria, N., R. Garrett, F. Gollnow, and K. Carlson. 2022. "Leakage Does Not Fully Offset Soy Supply-Chain Efforts to Reduce Deforestation in Brazil." *Nature Communications,* 13(1): 5476. https://doi.org/10.1038/s41467-022-33213-z.

Wang, Z., G.B. Martha, J. Liu, C.Z. Lima, and T.W. Hertel. 2024. "Planned Expansion of Transportation Infrastructure in Brazil Has Implications for the Pattern of Agricultural Production and Carbon Emissions." *Science of The Total Environment,* 928 (June): 172434. https://doi.org/10.1016/j.scitotenv.2024.172434.

Woltjer, G.B., M. Kuiper, A. Kavallari, H. van Meijl, J.P. Powell, M.M. Rutten, L.J. Shutes, and A.A. Tabeau. 2014. "The MAGNET Model: Module Description." LEI.

World Bank. 2024. "World Bank Open Data." https://data.worldbank.org/.

Yu, Q., L. You, U. Wood-Sichra, Y. Ru, A.K.B. Joglekar, S. Fritz, W. Xiong, M. Lu, W. Wu, and P. Yang. 2020. "A Cultivated Planet in 2010 – Part 2: The Global

Gridded Agricultural-Production Maps." *Earth System Science Data,* 12(4): 3545–72. https://doi.org/10.5194/essd-12-3545-2020.

Appendix A. Mathematical notes

This appendix provides detailed explanations about the five types of layers used in GTAP-SIMPLE-G: constant elasticity of substitution (CES) function, constant elasticity of transformation (CET) function, quantity-preserving CES (QCES), quantity-preserving CET (QCET), and perfect mobility (PM) across grid cells. It also derives solutions of these functions in percentage change form.

The most fundamental function used in GTAP-SIMPLE-G is the CES function. A CES production function with one output Y and N inputs X_i (i = 1, 2, …, N) takes the following functional form:

$$Q_Y = \alpha(\sum_{i=1}^{N} \delta_{X_i} Q_{X_i}{}^{-\rho})^{-\frac{1}{\rho}} \tag{A.1}$$

where Q_Y and Q_{X_i} represents the quantity of output and input X_i respectively, δ is the share parameter of each input, and its value equals the input's share in production cost at the baseline so $\sum_{i=1}^{N} \delta_{X_i} = 1$. In terms of parameters, α is the productivity parameter, ρ is a parameter related with σ, the elasticity of substitution between inputs, with $\sigma = \frac{1}{1+\rho}$. In CES function, $\sigma > 0$ and higher σ indicates the substitution between inputs in production is more elastic.

For a given value of Q_Y and a given vector of price for each input P_{X_i} (from the supply-demand equilibrium), the producer faces the problem of selecting the optimal usage of each X_i, in order to produce Q_Y with the minimal cost:

$$\begin{gathered} \min_{Q_{X_1},\dots,Q_{X_N}} \sum_{i=1}^{N} P_{X_i} Q_{X_i} \\ \text{subject to } Q_Y = \alpha(\sum_{i=1}^{N} \delta_i Q_{X_i}{}^{-\rho})^{-\frac{1}{\rho}} \end{gathered} \tag{A.2}$$

The optimal usage of X_i in level form is obtained by solving equation (A.2) analytically with the first order conditions, as a function of exogenous variables and parameters:

$$Q_{X_i} = (\frac{Q_Y}{\alpha})\left(\frac{\delta_{X_i}}{P_{X_i}}\right)^{\frac{1}{\rho+1}} (\sum_{i=1}^{N} \delta_{X_i}^{\frac{1}{\rho+1}} P_{X_i}^{\frac{\rho}{\rho+1}})^{\frac{1}{\rho}} \tag{A.3}$$

Equation (A.3) can be further simplified with the constant return to scale (CRTS) feature of CES function. According to CRTS, C_Y, the unit cost of Y, equals its average cost:

$$C_Y = \frac{\sum_{i=1}^{N} P_{X_i} Q_{X_i}}{Q_Y} = \frac{1}{\alpha}\left(\sum_{i=1}^{N} \delta_{X_i}^{\frac{1}{\rho+1}} P_{X_i}^{\frac{\rho}{\rho+1}}\right)^{\frac{\rho+1}{\rho}} \quad \text{(A.4)}$$

Then equation (A.3) can be rewritten with (A.4) and $\sigma = \frac{1}{1+\rho}$ as:

$$Q_{X_i} = Q_Y\left(\frac{\delta_{X_i} C_Y}{P_{X_i}}\right)^{\sigma} \alpha^{\sigma-1} \quad \text{(A.5)}$$

Based on the zero-profit condition for producers, C_Y also equals to the price of output Y, which can be regarded as exogenously given from the supply-demand equilibrium. Then equation (A.5) becomes a condensed analytical solution for the optimal usage of X_i .

To solve the model numerically with GEMPACK, it is necessary to convert the non-linear equation (A.5) to linearized form, by representing variables and parameters in level form with their percentage change form in response to exogenous shocks, represented with the hat notation (^). Following the linearization rule, the percentage change form of (A.5) can be written as:

$$\widehat{Q_{X_i}} = \widehat{Q_Y} - \hat{\alpha} - \widehat{\tau_{X_i}} - \sigma(\widehat{P_{X_i}} - \widehat{C_Y} - \hat{\alpha} - \widehat{\tau_{X_i}}) \quad \text{(A.6)}$$

where τ is the input-specific efficiency parameter and defined as $\widehat{\tau_{X_i}} = \frac{\sigma}{\sigma-1}\widehat{\delta_{X_i}}$.

When σ remains constant, equation (A.6) becomes a fully linearized function that connects the optimal usage of X_i with output, price, technology and substitution elasticities. The expansion of production scale ($\widehat{Q_Y} > 0$) requires more input usage. However, if the relative price growth in X_i is greater than Y ($\widehat{P_{X_i}} - \widehat{C_Y} > 0$), the producer will substitute X_i with other inputs, and the magnitude of such price effect can be amplified with higher σ. When production technology improves ($\hat{\alpha} > 0$), less input is required to produce the same amount of output. Finally, if the efficiency of input X_i decreases ($\widehat{\tau_{X_i}} < 0$), producers will require more X_i to compensate for the efficiency decline if the substitution between inputs is inelastic ($0 < \sigma < 1$, $(\sigma - 1)\widehat{\tau_{X_i}} > 0$), or use less X_i and more other inputs if the substitution between inputs is elastic ($\sigma > 1$).

Furthermore, the accounting relationship in GTAP requires all producers to satisfy zero-profit condition (Corong et al., 2017), which is represented in level term as:

$$P_Y Q_Y = C_Y Q_Y = \sum_{i=1}^{N} P_{X_i} Q_{X_i} \quad \text{(A.7)}$$

The percentage change form of (A.7) is

$$\widehat{P_Y} = \sum_{i=1}^{N} \frac{P_{X_i} Q_{X_i}}{P_Y Q_Y} \widehat{P_{X_i}} \quad \text{(A.8)}$$

This equation indicates that in the CES function, the percentage change in output price equals the sum of percentage change of input prices, weighted by each input's cost share. Equations (A.6) and (A.8) together form the CES layer implemented in GTAP-SIMPLE-G, which governs quantity and price relationship in the production from multiple inputs to a single output.

Although the CES function preserves the value, the sum of input quantity may not necessarily equal its output quantity, which causes biased results when aggregating the same commodity from different sources or locations (M. Horridge 2019). To maintain total quantity, one possible approach is to replace the cost share in equation (A.8) with the quantity share of each input:

$$\widehat{P_Y} = \sum_{i=1}^{N} \frac{Q_{X_i}}{Q_Y} \widehat{P_{X_i}} \quad \text{(A.9)}$$

Equation (A.6) and (A.9) form a variant of CES function that preserves the quantity, named QCES.

In contrast to a CES function, a CET function allocates a single input to multiple outputs while preserving the value. Mathematically, CET and CES functions take the same equational form, with the only difference that σ, now representing the elasticity of transformation, should be negative. So, a CET layer is also represented by equations (A.6) and (A.8). Similarly, a QCET layer preserves the sum of output quantity to equal its input quantity. This feature is important in land use allocation system because it guarantees the balance of land area before and after the allocation. The equations of a QCET layer take the same form as a QCES layer (A.6 and A.9).

Finally, when all inputs are perfect substitutes for one another, the CES function collapses to a linear additive function. In GTAP-SIMPLE-G, this linear function is used to represent the spatial aggregation of labor, capital and intermediate inputs between the local and regional level. Given that GTAP-SIMPLE-G is a static model that simulates the change between two equilibria before and after exogenous shocks, it is reasonable to assume that those inputs are perfectly mobile not only across activities but also across grid cells, and the price over all grid cells are uniform at the equilibrium.

In model implementation, the perfect mobility layer of input X^{PM} is represented with the following equations:

$$\widehat{P_{X_g^{PM}}} = \widehat{P_{X_r^{PM}}} \tag{A.10}$$

$$\widehat{Q_{X_r^{PM}}} = \sum_g \frac{P_{X_g^{PM}} Q_{X_g^{PM}}}{P_{X_r^{PM}} Q_{X_r^{PM}}} \widehat{Q_{X_g^{PM}}} = \sum_g \frac{Q_{X_g^{PM}}}{Q_{X_r^{PM}}} \widehat{Q_{X_g^{PM}}} \tag{A.11}$$

where g is the index of grid cells, and r is the index of the focus region that all grid cells g belongs to.

Appendix B. Additional notes on GTAP-SIMPLE-G model

This appendix provides the list of variables and parameters introduced to the GTAP framework in GTAP-SIMPLE-G. For the list of variables of GTAP framework, please refers to Table A.4 in Corong et al. (2017).

Table B.1. List of variables introduced in GTAP-SIMPLE-G.

Variable	Dimension	Description
QFORESTg	g	Quantity of forestland by grid (g)
p_PFORESTg	g	Price of forestland by grid
QPLANDg	g	Quantity of pasture by grid
p_PPLANDg	g	Price of pasture by grid
QLANDgl	g,l	Quantity of cropland grid and irrigation (l) type (ltype)
p_PLANDgl	g,l	Price of cropland by grid and ltype
p_QLANDg	g	Quantity of cropland by grid
p_PLANDg	g	Price of cropland by grid
p_PLCOMg*	g	QCET price of cropland by grid
p_QCPLANDg	g	Quantity of pasture and cropland by grid
p_PCPLANDg	g	Price of pasture and cropland by grid
p_PCPLCOMg*	g	QCET price of pasture and cropland by grid
p_QTLANDg	g	Quantity of total land used (forest plantation, pasture, cropland) by grid
p_PTLANDg	g	Price of total land used by grid
p_PTLCOMg*	g	QCET price of total land used by grid
p_QFORESTr	G	Quantity of forest plantation in gridded region
p_PFORESTr	G	Price of forest plantation in gridded region
p_PFORCOMr*	G	QCES price of forest plantation in gridded region
p_QPLANDr	G	Quantity of pasture in gridded region
p_PPLANDr	G	Price of pasture in gridded region
p_PPLCOMr*	G	QCES price of pasture in gridded region
p_QPLANDra	G, NCACT	Quantity of pasture use by activities in gridded region
p_PPLANDra	G, NCACT	Price of pasture use by activities in gridded region
p_PPLCOMra*	G	QCET price of pasture use by activities in gridded region
p_QLANDr	G	Quantity of cropland for gridded region r
p_PLANDr	G	Price of cropland for gridded region r

(Continued…)

Table B.1. List of variables introduced in GTAP-SIMPLE-G. (…Continued)

Variable	Dimension	Description
p_AOCROPgl	g,l	Input-neutral efficiency index in crop prod. by grid & ltype
p_AFINTgl	g,l	Intermediate input efficiency index in crop prod. by grid & ltype
p_AFLABORgl	g,l	Labor efficiency index in crop prod. by grid & ltype
p_AFCAPgl	g,l	Capital efficiency index in crop prod. by grid & ltype
p_AFLANDgl	g,l	Land efficiency index in crop prod. by grid & ltype
p_AFWATERgl	g,l	Aggregate irrigation efficiency index in crop prod. by grid & ltype
p_AFWATSGgl	g,l	Water efficiency index in crop prod. by grid & ltype
p_AFWATEQgl	g,l	Water equipment efficiency index in crop prod. by grid & ltype
p_AOCROPg	g	Input-neutral efficiency index in crop prod. by grid
p_AFINTg	g	Intermediate input efficiency index in crop prod. by grid
p_AFLABORg	g	Labor efficiency index in crop prod. by grid
p_AFCAPg	g	Capital efficiency index in crop prod. by grid
p_AFLANDg	g	Land efficiency index in crop prod. by grid
p_AFWATERg	g	Aggregate irrigation efficiency index in crop prod. by grid
p_AFWATSGg	g	Water efficiency index in crop prod. by grid
p_AFWATEQg	g	Water equipment efficiency index in crop prod. by grid
p_AOCROPrl	G, l	Input-neutral efficiency index in crop prod. by reg & ltype
p_AFINTrl	G, l	Intermediate input efficiency index in crop prod. by reg & ltype
p_AFLABORrl	G, l	Labor efficiency index in crop prod. by reg & ltype
p_AFCAPrl	G, l	Capital efficiency index in crop prod. by reg & ltype
p_AFLANDrl	G, l	Land efficiency index in crop prod. by reg & ltype
p_AFWATERrl	G, l	Aggregate irrigation efficiency index in crop prod. by reg & ltype
p_AFWATSGrl	G, l	Water efficiency index in crop prod. by reg & ltype
p_AFWATEQrl	G, l	Water equipment efficiency index in crop prod. by reg & ltype
p_AOCROPr	G	Input-neutral efficiency index in crop prod. by region
p_AFINTr	G	Intermediate input efficiency index in crop prod. by region

(Continued…)

Table B.1. List of variables introduced in GTAP-SIMPLE-G. (…Continued)

Variable	Dimension	Description
p_AFLABORr	G	Labor efficiency index in crop prod. by region
p_AFCAPr	G	Capital efficiency index in crop prod. by region
p_AFLANDr	G	Land efficiency index in crop prod. by region
p_AFWATERr	G	Aggregate irrigation efficiency index in crop prod. by region
p_AFWATSGr	G	Water efficiency index in crop prod. by region
p_AFWATEQr	G	Water equipment efficiency index in crop prod. by region
p_AOCROP	g,l	Input-neutral efficiency index in crop prod. by grid & ltype (aggregated from grid, grid & ltype, region, region & ltype levels)
p_AFINT	g,l	Intermediate input efficiency index in crop prod. by grid & ltype (aggregated from grid, grid & ltype, region, region & ltype levels)
p_AFLABOR	g,l	Labor efficiency index in crop prod. by grid & ltype (aggregated from grid, grid & ltype, region, region & ltype levels)
p_AFCAP	g,l	Capital efficiency index in crop prod. by grid & ltype (aggregated from grid, grid & ltype, region, region & ltype levels)
p_AFLAND	g,l	Land efficiency index in crop prod. by grid & ltype (aggregated from grid, grid & ltype, region, region & ltype levels)
p_AFWATER	g,l	Aggregate irrigation efficiency index in crop prod. by grid & ltype (aggregated from grid, grid & ltype, region, region & ltype levels)
p_AFWATSG	g,l	Water efficiency index in crop prod. by grid & ltype (aggregated from grid, grid & ltype, region, region & ltype levels)
p_AFWATEQ	g,l	Water equipment efficiency index in crop prod. by grid & ltype (aggregated from grid, grid & ltype, region, region & ltype levels)
QWATSGgl	g,l	Quantity of irrigation water use by grid & lytpe
p_PWATSGgl	g,l	Price of irrigation water use by grid & lytpe
p_QWATEQgl	g,l	Quantity of irrigation eqpt by grid & lytpe
p_PWATEQgl	g,l	Price of irrigation equipment by grid & lytpe
p_QWATERgl	g,l	Quantity of irrigation water + equipment by grid & lytpe
p_PWATERgl	g,l	Price of irrigation water + equipment by grid & lytpe
p_QWATSGr	G	Quantity of irrigation water for gridded region r

(Continued…)

Table B.1. List of variables introduced in GTAP-SIMPLE-G. (…Continued)

Variable	Dimension	Description
p_PWATSGr	G	Price of irrigation water for gridded region r
p_QLANDWTRgl	g,l	Quantity of land+irrigation by grid & ltype
p_PLANDWTRgl	g,l	Price of land+irrigation by grid & ltype
p_QLABORgl	g,l	Labor input by grid & ltype
p_PLABORgl	g,l	Price of labor input by grid & ltype
p_QCAPgl	g,l	Capital input by grid & ltype
p_PCAPgl	g,l	Price of capital input by grid & ltype
p_PNLANDgl	g,l	Price of labor + capital by grid & ltype
p_QNLANDgl	g,l	Quantity of labor + capital by grid & ltype
p_PAUGLANDgl	g,l	Price of augmented land by grid & ltype
p_QAUGLANDgl	g,l	Quantity of augmented land by grid & ltype
p_QINTgl	g,l	Quantity of intermediate input
p_PINTgl	g,l	Price of intermediate input
p_QCROPgl	g,l	Quantity of forest plantation in gridded region
p_PCROPgl	g,l	Price of forest plantation in gridded region
p_PCROPr	G	Price of aggregated crop
p_QCROPr	G	Quantity of aggregated crop
p_QMCROPglc	g,l,c	Quantity of multiple crops by grid & ltype
p_PMCROPglc	g,l,c	Price of multiple crops by grid & ltype
p_AFQMCROPgc	g,c	Technical parameter for crop-specific production
s_QWATEQg	g	Slack to control irrigation equipment by grid
p_QLABORr	G	Quantity of labor at regional level
p_PLABORr	G	Price of labor at regional level
p_QCAPr	G	Quantity of capital at regional level
p_PCAPr	G	Price of capital at regional level
p_QINTr	G	Quantity of intermediate input at regional level
p_PINTr	G	Price of intermediate input at regional level
p_QMCROPrc	G,c	Quantity of multiple crop by region
p_PMCROPrc	G,c	Price of multiple crop by region
p_PMCRPCOMrc*	G,c	QCET price of multiple crop by region
t_pb	CACT,G	Tax variable to represent the difference between MAKEB and MAKES for cultivation

Notes: Indexes in dimensions: g: grid cell; l: irrigation type; c: crop; G: Gridded region (subset of GTAP regions); NCACT: non-cultivation activities; CACT: cultivation activity. Variables with asterisk (*) refer to those included in the default version (employing QCET / QCES) only.

Source: Author code.

Table B.2. List of parameters introduced in GTAP-SIMPLE-G.

Parameter	Dimension	Description
ISIRRI	l	Dummy for Irrigated
ETRAFCPg	g	Elasticity. of transformation between cropland & pasture and forest plantation by grid
ETRACPg	g	Elasticity of transformation between cropland and pasture by grid
ETRALANDg	g	Elasticity of transformation between irrigated and rainfed cropland by grid
ESUBFg	g	Elasticity of substitution between forest plantation supply by grid
ESUBPg	g	Elasticity of substitution between pasture supply by grid
ETRAPLra	G	Elasticity of transformation for pasture use by region
ESUBWgl	g,l	Elasticity of substitution in irrigation water & equipment CES nest by grid & ltype
EIRRIGgl	g,l	Elasticity. of substitution between land & water by grid
ENLANDgl	g,l	Elasticity. of substitution in non-land CES nest by grid & ltype
EAUGLANDgl	g,l	Elasticity. of substitution in augmented land. CES nest by grid & ltype
ECROPgl	g,l	Elasticity of substitution in crop production by grid & ltype
ETRANSMC	g,l	Transformation elasticity between multiple crops by grid & ltype
EWATEQgl	g,l	Supply elasticity of irrigation equipment by region
ESUBMC	G,c	Elasticity of substitution for multiple crops across grids by region

Notes: Indexes in dimensions: g: grid cell; l: irrigation type; c: crop; G: Gridded region (subset of GTAP regions).

Source: Author code.

Appendix C. Mapping across datasets

Table C.1. Mapping between GTAP and GTAP-SIMPLE-G regions.

GTAP-SIMPLE-G region	Description	GTAP regions
Oceania	Australia, New Zealand	Australia; New Zealand; Rest of Oceania.
China	Mainland China	China.
EastAsia	East Asia (except Mainland China)	China, Hong Kong SAR; Japan; Republic of Korea; Mongolia; Taiwan Province of China; Rest of East Asia; Brunei Darussalam.
SEAsia	Southeast Asia	Cambodia; Indonesia; Lao People's Democratic Republic; Malaysia; Philippines; Singapore; Thailand; Viet Nam; Rest of Southeast Asia.
SouthAsia	South Asia	Afghanistan; Bangladesh; India; Nepal; Pakistan; Sri Lanka; Rest of South Asia.
USA	USA	United States of America.
NAmerica	North America (except USA)	Canada; Mexico; Rest of North America.
Brazil	Brazil	Brazil.
LatinAmer	Latin America (except Brazil)	Argentina; Bolivia (Plurinational State o; Chile; Colombia; Ecuador; Paraguay; Peru; Uruguay; Venezuela (Bolivarian Republic; Rest of South America; Costa Rica; Guatemala; Honduras; Nicaragua; Panama; El Salvador; Rest of Central America; Dominican Republic; Haiti; Jamaica; Puerto Rico; Trinidad and Tobago; Caribbean.
WestEurope	Western Europe	Austria; Belgium; Bulgaria; Croatia; Cyprus; Czechia; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Romania; Slovakia; Slovenia; Spain; Sweden; United Kingdom of Great Britain; Switzerland; Norway; Rest of EFTA.
MENA	Middle East and North Africa	Bahrain; Iran (Islamic Republic of); Iraq; Israel; Jordan; Kuwait; Lebanon; Oman; Palestine; Qatar; Saudi Arabia; Syrian Arab Republic; Türkiye; United Arab Emirates; Rest of Western Asia; Algeria; Egypt; Morocco; Tunisia; Rest of North Africa.

(Continued...)

Table C.1. Mapping between GTAP and GTAP-SIMPLE-G regions. (…Continued)

GTAP-SIMPLE-G region	Description	GTAP regions
SSA	Sub-Saharan Africa	Benin; Burkina Faso; Cameroon; Côte d'Ivoire; Ghana; Guinea; Mali; Niger; Nigeria; Senegal; Togo; Rest of Western Africa; Central African Republic; Chad; Congo; Democratic Republic of the Con; Equatorial Guinea; Gabon; South-Central Africa; Comoros; Ethiopia; Kenya; Madagascar; Malawi; Mauritius; Mozambique; Rwanda; Sudan; United Republic of Tanzania; Uganda; Zambia; Zimbabwe; Rest of Eastern Africa; Botswana; Eswatini; Namibia; South Africa; Rest of Southern African Customs Union.
RestofWorld	Rest of World	Albania; Serbia; Belarus; Russian Federation; Ukraine; Rest of Eastern Europe; Rest of Europe; Kazakhstan; Kyrgyzstan; Tajikistan; Uzbekistan; Rest of Former Soviet Union; Armenia; Azerbaijan; Georgia; Rest of the World.

Source: The 10 by 10 GTAP regional concordances come from GTAPAgg's default aggregation file, with the US, Brazil and China classified separately.

Table C.2. Mapping between GTAP and GTAP-SIMPLE-G regions.

GTAP-SIMPLE-G activities	Description	GTAP activities
Cultivation	Crop production activities	Rice; Wheat; Other grains; Vegetable & fruits; Oilseeds; Sugar crops; Plant-based fibers; Other crops.*
Cattle	Cattle	Bovine cattle, sheep and goats.
OtherLvStock	Other Animal Products	Animal products nec.
CattleMeat	Cattle Meat	Bovine meat products.
OtherMeat	Other Meat	Meat products nec.
RawMilk	Raw milk	Raw milk.
Wool	Wool	Wool, silk-worm cocoons.
Forestry	Forestry	Forestry.
Fishing	Fishing	Fishing.
Extraction	Mining and Extraction	Coal; Oil; Gas; Minerals nec.
ProcRice	Processed rice	Processed rice.
VegOil	Vegetable oils and fats	Vegetable oils and fats.
DairyProd	Dairy products	Dairy products.
Sugar	Sugar	Sugar.
BevTobacco	Beverages and tobacco products	Beverages and tobacco products.
OtherProcFd	Other processed Food	Food products nec.
TextWapp	Textiles and Clothing	Textiles; Wearing apparel.
LightMnfc	Light Manufacturing	Leather products; Wood products; Paper products, publishing; Metal products; Motor vehicles and parts; Transport equipment nec; Manufactures nec.
HeavyMnfc	Heavy Manufacturing	Petroleum, coal products; Chemical products; Basic pharmaceutical products; Rubber and plastic products; Mineral products nec; Ferrous metals; Metals nec; Computer, electronic and optic; Electrical equipment; Machinery and equipment nec.
Util_Cons	Utilities and Construction	Electricity; Gas manufacture, distribution; Water; Construction.

(Continued...)

Table C.2. Mapping between GTAP and GTAP-SIMPLE-G regions. (…Continued)

GTAP-SIMPLE-G activities	Description	GTAP activities
TransComm	Transport and Communication	Trade; Accommodation, Food and service; Transport nec; Water transport; Air transport; Warehousing and support activities; Communication.
OthServices	Other Services	Financial services nec; Insurance; Real estate activities; Business services nec; Recreational and other service; Other Services (Government); Education; Human health and social work a; Dwellings.

Source: The 10 by 10 GTAP sectoral concordances come from GTAPAgg's default aggregation file, with activities relevant to livestock and processed agricultural commodities classified separately.

Table C.3. Mapping between GTAP and GTAP-SIMPLE-G factors.

GTAP-SIMPLE-G factors	Description	GTAP factors
Land	Land	Land
Labor	Labor	Technicians/Associate Professional; Clerks, Service/Shop workers; Officials and Managers; Agricultural and Unskilled.
Capital	Capital	Capital.
NatRes	Natural resource	Natural resource.

Source: Author classification.

Table C.4. Mapping between MapBiomas and GTAP-SIMPLE-G land use categories.

GTAP-SIMPLE-G land use categories	MapBiomas land use categories	Used by GTAP-SIMPLE-G activities
Natural forest	Natural forest	N/A
Forest plantation	Forest plantation	Forestry
Non-forest vegetation	Wetland; grassland; salt flat; rocky outcrop; other non-forest natural formation.	N/A
Pasture	Pasture.	Cattle; OtherLvStock; RawMilk; Wool.
Cropland	Agriculture; mosaic of agriculture and pasture.	Cultivation
Urban infrastructure	Urban infrastructure.	N/A
Other non-vegetated area	Beach and dune; mining; other non-vegetated area.	N/A
Water	River, lake and ocean; aquaculture	N/A

Notes: MapBiomas land use categories are based on its level 2 classification.

Source: Author classification.

Table C.5. Mapping between FAO, SPAM2010 and GTAP crops.

FAO	FAO (CPC21)	SPAM2010	GTAP
Wheat	Wheat	Wheat	Wheat
Rice, paddy	Rice	Rice	Rice
Barley	Barley	Barley	Other grains
Maize	Maize (corn)	Maize	Other grains
Rye	Rye	Other cereals	Other grains
Oats	Oats	Other cereals	Other grains
Millet	Millet	Pearl Millet / Small Millet	Other grains
Sorghum	Sorghum	Sorghum	Other grains
Buckwheat	Buckwheat	Other cereals	Other grains
Quinoa	Quinoa	Other cereals	Other grains
Fonio	Fonio	Other cereals	Other grains
Triticale	Triticale	Other cereals	Other grains

(Continued...)

Table C.5. Mapping between FAO, SPAM2010 and GTAP crops. (…Continued)

FAO	FAO (CPC21)	SPAM2010	GTAP
Canary seed	Canary seed	Other cereals	Other grains
Grain, mixed	Mixed grain	Other cereals	Other grains
Cereals, nes	Cereals n.e.c	Other cereals	Other grains
Potatoes	Potatoes	Potato	Vegetable & fruits
Sweet potatoes	Sweet potatoes	Sweet potato	Vegetable & fruits
Cassava	Cassava	Cassava	Vegetable & fruits
Yautia (cocoyam)	Yautia	Other roots	Vegetable & fruits
Taro (cocoyam)	Taro	Other roots	Vegetable & fruits
Yams	Yams	Yams	Vegetable & fruits
Roots and tubers, nes	Edible roots and tubers with high starch	Other roots	Vegetable & fruits
Sugar cane	Sugar cane	Sugarcane	Sugar crops
Sugar beet	Sugar beet	Sugarbeet	Sugar crops
Sugar crops, nes	Other sugar crops n.e.c.	Rest of crops	Sugar crops
Beans, dry	Beans, dry	Bean	Vegetable & fruits
Broad beans, horse beans, dry	Broad beans and horse beans, dry	Other pulses	Vegetable & fruits
Peas, dry	Peas, dry	Other pulses	Vegetable & fruits
Chick peas	Chick peas, dry	Chickpea	Vegetable & fruits
Cow peas, dry	Cow peas, dry	Cowpea	Vegetable & fruits
Pigeon peas	Pigeon peas, dry	Pigeonpea	Vegetable & fruits
Lentils	Lentils, dry	Lentil	Vegetable & fruits
Bambara beans	Bambara beans, dry	Other pulses	Vegetable & fruits
Vetches	Vetches	Other pulses	Vegetable & fruits

(Continued...)

Table C.5. Mapping between FAO, SPAM2010 and GTAP crops. (…Continued)

FAO	FAO (CPC21)	SPAM2010	GTAP
Lupins	Lupins	Other pulses	Vegetable & fruits
Pulses, nes	Other pulses n.e.c.	Other pulses	Vegetable & fruits
Brazil nuts, with shell	Brazil nuts, in shell	Rest of crops	Vegetable & fruits
Cashew nuts, with shell	Cashew nuts, in shell	Rest of crops	Vegetable & fruits
Chestnut	Chestnuts, in shell	Rest of crops	Vegetable & fruits
Almonds, with shell	Almonds, in shell	Rest of crops	Vegetable & fruits
Walnuts, with shell	Walnuts, in shell	Rest of crops	Vegetable & fruits
Pistachios	Pistachios, in shell	Rest of crops	Vegetable & fruits
Kola nuts	Kola nuts	Rest of crops	Vegetable & fruits
Hazelnuts, with shell	Hazelnuts, in shell	Rest of crops	Vegetable & fruits
Areca nuts	Areca nuts	Rest of crops	Vegetable & fruits
Nuts, nes	Other nuts	Rest of crops	Vegetable & fruits
Soybeans	Soya beans	Soybean	Oilseeds
Groundnuts, with shell	Groundnuts, excluding shelled	Groundnut	Oilseeds
Coconuts	Coconuts, in shell	Coconut	Oilseeds
Oil palm fruit	Oil palm fruit	Oilpalm	Oilseeds
Palm kernels	Palm kernels	Oilpalm	Oilseeds
Olives	Olives	Other oil crops	Oilseeds
Karite nuts (sheanuts)	Karite nuts (sheanuts)	Other oil crops	Oilseeds
Castor oil seed	Castor oil seeds	Other oil crops	Oilseeds
Sunflower seed	Sunflower seed	Sunflower	Oilseeds
Rapeseed	Rapeseed or colza seed	Rapeseed	Oilseeds
Tung nuts	Tung nuts	Other oil crops	Oilseeds
Jojoba seed	Jojoba seeds	Other oil crops	Oilseeds
Safflower seed	Safflower seed	Other oil crops	Oilseeds
Sesame seed	Sesame seed	Sesameseed	Oilseeds
Mustard seed	Mustard seed	Rapeseed	Oilseeds

(Continued...)

Table C.5. Mapping between FAO, SPAM2010 and GTAP crops. (…Continued)

FAO	FAO (CPC21)	SPAM2010	GTAP
Poppy seed	Poppy seed	Other oil crops	Oilseeds
Melonseed	Melonseed	Other oil crops	Oilseeds
Tallowtree seed	Tallowtree seeds	Other oil crops	Oilseeds
Kapok fruit	Kapok fruit	Other oil crops	Oilseeds
Kapokseed in shell	Kapokseed in shell	Other oil crops	Oilseeds
Seed cotton	Seed cotton, unginned	Cotton	Plant-based fibers
Cottonseed	Cottonseed	Other oil crops	Oilseeds
Linseed	Linseed	Other oil crops	Oilseeds
Hempseed	Hempseed	Other oil crops	Oilseeds
Oilseeds nes	Other oil seeds, n.e.c.	Other oil crops	Oilseeds
Cabbages and other brassicas	Cabbages	Vegetables	Vegetable & fruits
Artichokes	Artichokes	Vegetables	Vegetable & fruits
Asparagus	Asparagus	Vegetables	Vegetable & fruits
Lettuce and chicory	Lettuce and chicory	Vegetables	Vegetable & fruits
Spinach	Spinach	Vegetables	Vegetable & fruits
Cassava leaves	Cassava leaves	Vegetables	Vegetable & fruits
Tomatoes	Tomatoes	Vegetables	Vegetable & fruits
Cauliflowers and broccoli	Cauliflowers and broccoli	Vegetables	Vegetable & fruits
Pumpkins, squash and gourds	Pumpkins, squash and gourds	Vegetables	Vegetable & fruits
Cucumbers and gherkins	Cucumbers and gherkins	Vegetables	Vegetable & fruits
Eggplants (aubergines)	Eggplants (aubergines)	Vegetables	Vegetable & fruits
Chillies and peppers, green	Chillies and peppers, green (Capsicum spp. and Pimenta spp.)	Vegetables	Vegetable & fruits
Onions, shallots, green	Onions and shallots, green	Vegetables	Vegetable & fruits

(Continued...)

Table C.5. Mapping between FAO, SPAM2010 and GTAP crops. (…Continued)

FAO	FAO (CPC21)	SPAM2010	GTAP
Onions, dry	Onions and shallots, dry	Vegetables	Vegetable & fruits
Garlic	Green garlic	Vegetables	Vegetable & fruits
Leeks, other alliaceous vegetables	Leeks and other alliaceous vegetables	Vegetables	Vegetable & fruits
Beans, green	Other beans, green	Vegetables	Vegetable & fruits
Peas, green	Peas, green	Vegetables	Vegetable & fruits
Vegetables, leguminous nes	Broad beans and horse beans, green	Vegetables	Vegetable & fruits
String beans	String beans	Vegetables	Vegetable & fruits
Carrots and turnips	Carrots and turnips	Vegetables	Vegetable & fruits
Okra	Okra	Vegetables	Vegetable & fruits
Maize, green	Green corn (maize)	Vegetables	Vegetable & fruits
Mushrooms and truffles	Mushrooms and truffles	Vegetables	Vegetable & fruits
Chicory roots	Chicory roots	Vegetables	Other Crops
Carobs	Locust beans (carobs)	Vegetables	Vegetable & fruits
Vegetables, fresh nes	Other vegetables, fresh, n.e.c	Vegetables	Vegetable & fruits
Bananas	Bananas	Banana	Vegetable & fruits
Plantains and others	Plantains and cooking bananas	Plantain	Vegetable & fruits
Oranges	Oranges	Tropical fruit	Vegetable & fruits
Tangerines, mandarins, clementines, satsumas	Tangerines, mandarins, clementines	Tropical fruit	Vegetable & fruits
Lemons and limes	Lemons and limes	Tropical fruit	Vegetable & fruits

(Continued...)

Table C.5. Mapping between FAO, SPAM2010 and GTAP crops. (…Continued)

FAO	FAO (CPC21)	SPAM2010	GTAP
Grapefruit (inc. pomelos)	Pomelos and grapefruits	Tropical fruit	Vegetable & fruits
Fruit, citrus nes	Other citrus fruit, n.e.c.	Tropical fruit	Vegetable & fruits
Apples	Apples	Temperate fruit	Vegetable & fruits
Pears	Pears	Temperate fruit	Vegetable & fruits
Quinces	Quinces	Temperate fruit	Vegetable & fruits
Apricots	Apricots	Temperate fruit	Vegetable & fruits
Cherries, sour	Sour cherries	Temperate fruit	Vegetable & fruits
Cherries	Cherries	Temperate fruit	Vegetable & fruits
Peaches and nectarines	Peaches and nectarines	Temperate fruit	Vegetable & fruits
Plums and sloes	Plums and sloes	Temperate fruit	Vegetable & fruits
Fruit, stone nes	Other stone fruits	Temperate fruit	Vegetable & fruits
Fruit, pome nes	Other pome fruits	Temperate fruit	Vegetable & fruits
Strawberries	Strawberries	Temperate fruit	Vegetable & fruits
Raspberries	Raspberries	Temperate fruit	Vegetable & fruits
Gooseberries	Gooseberries	Temperate fruit	Vegetable & fruits
Currants	Currants	Temperate fruit	Vegetable & fruits
Blueberries	Blueberries	Temperate fruit	Vegetable & fruits
Cranberries	Cranberries	Temperate fruit	Vegetable & fruits
Berries nes	Other berries and fruits of the genus	Temperate fruit	Vegetable & fruits

(Continued...)

Table C.5. Mapping between FAO, SPAM2010 and GTAP crops. (…Continued)

FAO	FAO (CPC21)	SPAM2010	GTAP
Grapes	Grapes	Temperate fruit	Vegetable & fruits
Watermelons	Watermelons	Tropical fruit	Vegetable & fruits
Melons, other (inc.cantaloupes)	Cantaloupes and other melons	Tropical fruit	Vegetable & fruits
Figs	Figs	Tropical fruit	Vegetable & fruits
Mangoes, mangosteens, guavas	Mangoes, guavas and mangosteens	Tropical fruit	Vegetable & fruits
Avocados	Avocados	Tropical fruit	Vegetable & fruits
Pineapples	Pineapples	Tropical fruit	Vegetable & fruits
Dates	Dates	Tropical fruit	Vegetable & fruits
Persimmons	Persimmons	Tropical fruit	Vegetable & fruits
Cashewapple	Cashewapple	Tropical fruit	Vegetable & fruits
Kiwi fruit	Kiwi fruit	Temperate fruit	Vegetable & fruits
Papayas	Papayas	Tropical fruit	Vegetable & fruits
Fruit, tropical fresh nes	Other tropical and subtropical fruits, n.e.c.	Tropical fruit	Vegetable & fruits
Fruit, fresh nes	Other fruits, n.e.c.	Temperate fruit	Vegetable & fruits
Coffee, green	Coffee, green	Arabica coffee / Robusta coffee	Other Crops
Cocoa, beans	Cocoa beans	Cocoa	Other Crops
Tea	Tea leaves	Tea	Other Crops
Maté	Maté leaves	Rest of crops	Other Crops
Hops	Hop cones	Rest of crops	Other Crops

(Continued...)

Table C.5. Mapping between FAO, SPAM2010 and GTAP crops. (…Continued)

FAO	FAO (CPC21)	SPAM2010	GTAP
Pepper (piper spp.)	Pepper (Piper spp.), raw	Rest of crops	Other Crops
Chillies and peppers, dry	Chillies and peppers, dry (Capsicum spp., Pimenta spp.), raw	Rest of crops	Other Crops
Vanilla	Vanilla, raw	Rest of crops	Other Crops
Cinnamon (canella)	Cinnamon and cinnamon-tree flowers, raw	Rest of crops	Other Crops
Cloves	Cloves (whole stems), raw	Rest of crops	Other Crops
Nutmeg, mace and cardamoms	Nutmeg, mace, cardamoms, raw	Rest of crops	Other Crops
Anise, badian, fennel, coriander	Anise, badian, coriander, cumin, caraway, fennel and juniper berries, raw	Rest of crops	Other Crops
Ginger	Ginger, raw	Rest of crops	Other Crops
Spices, nes	Other stimulant, spice and aromatic crops, n.e.c.	Rest of crops	Other Crops
Peppermint	Peppermint, spearmint	Rest of crops	Other Crops
Pyrethrum, dried	Pyrethrum, dried flowers	Rest of crops	Other Crops
Cotton lint	Cotton lint, ginned	Cotton	Plant-based fibers
Flax fibre and tow	Flax, raw or retted	Other fibre crops	Plant-based fibers
Hemp tow waste	True hemp, raw or retted	Other fibre crops	Plant-based fibers
Kapok fibre	Kapok fibre, raw	Other fibre crops	Plant-based fibers
Jute	Jute, raw or retted	Other fibre crops	Plant-based fibers
Bastfibres, other	Kenaf, and other textile bast fibres	Other fibre crops	Plant-based fibers
Ramie	Ramie, raw or retted	Other fibre crops	Plant-based fibers

(Continued...)

Table C.5. Mapping between FAO, SPAM2010 and GTAP crops. (…Continued)

FAO	FAO (CPC21)	SPAM2010	GTAP
Sisal	Sisal, raw	Other fibre crops	Plant-based fibers
Agave fibres nes	Agave fibres, raw, n.e.c.	Other fibre crops	Plant-based fibers
Manila fibre (abaca)	Abaca, manila hemp, raw	Other fibre crops	Plant-based fibers
Coir	Coir, raw	Other fibre crops	Plant-based fibers
Fibre crops nes	Other fibre crops, raw, n.e.c	Other fibre crops	Plant-based fibers
Tobacco, unmanufactured	Unmanufactured tobacco	Tobacco	Other Crops
Rubber, natural	Natural rubber in primary forms	Rest of crops	Other Crops

Notes: The classification of chicory roots is inconsistent between SPAM2010 (as vegetables) and GTAP (as other crops). Although this inconsistency does not matter in this study since both the crop output and crop price data do not contain chicory roots produced in Brazil, it may be worth the attention of researchers working on other regions.

Source: The mapping between FAO and SPAM2010 crops (Yu et al., 2020) uses FAO item code, while the mapping between FAO and GTAP crops (Chepeliev, 2020) and the current FAOSTAT database (Food and Agriculture Organization of the United Nations, 2023) use the Central Product Classification (CPC) (version 2.1) code, which is mapped with FAO item code following Hofste (2019).

Appendix D. Supplementary notes on the gridded data in Brazil

In this study, MapBiomas was selected as the data source for gridded land use. Besides MapBiomas, the MODIS land use dataset (Friedl and Sulla-Menashe, 2019) provides multi-category land use data globally at a 500 meter resolution since 2001. Although the pattern of cropland in MapBiomas and MODIS are similar locally, the national sum of cropland area from MapBiomas aligns better with the data from FAOSTAT (Food and Agriculture Organization of the United Nations, 2023).

As to the data source for gridded crop output, besides the SPAM2010 dataset used in this study, comparisons were made with several other gridded datasets that provide crop production data. The GGCP10 dataset (X. Qin et al., 2023) contains gridded crop production data for four crops (maize, wheat, rice, and soybean) at a resolution of 10 kilometers from 2010 to 2020. Although this dataset includes data for the baseline year 2017, it does not provide information on sugar cane, which represents a significant portion of Brazilian cropland usage. Additionally, it does not distinguish outputs by irrigation types, which is essential for the irrigation subsystems in GTAP-SIMPLE-G. Alternatively, the GAEZ+ dataset (Grogan et al., 2022) contains gridded harvest area, crop production and yield data for 26 crops in 2015 at a resolution of 5 arcminute; and the SPAM2020 dataset (International Food Policy Research Institute, 2024) updates the SPAM2010 dataset to 2020 and increases the number of included crops from 42 to 46.

To select the most suitable gridded crop production dataset for GTAP-SIMPLE-G, the spatial patterns of cropland area data from GAEZ+, SPAM2010 and SPAM2020 were compared with those from MapBiomas.[21]If a dataset's cropland area does not align with the gridded land use data, it may result in unreasonable yield pattern. The harvest area data from GAEZ+ is centered around 3000 ha and shows minimal variance at the spatial level, significantly lower than the physical cropland area in agricultural hotspots (6000 ha and above). This discrepancy indicates an inconsistency between GAEZ+ and MapBiomas. In contrast, the cropland pattern from both SPAM2010 and SPAM2020 align more closely with MapBiomas, but some unusual patterns were also identified in the current version of SPAM2020.[22] Therefore, SPAM2010 was selected as the data source for gridded crop production in this study.

[21] In comparison, cropland area is summed over all crops and irrigation types at gridded level. For GAEZ+, the harvest area is used since physical area is not available.

[22] According to SPAM2020, in certain grid cells of the Paraná state, the physical cropland area exceeds the total physical area of that grid cell. Also, in Rio Grande do Sul, Mato Grosso, Paraná and Goiás states, some hollows (grids with cropland area close to 0 ha) were found in the span of grid cells with 4000 or higher ha of cropland, which is not shown in MapBiomas.

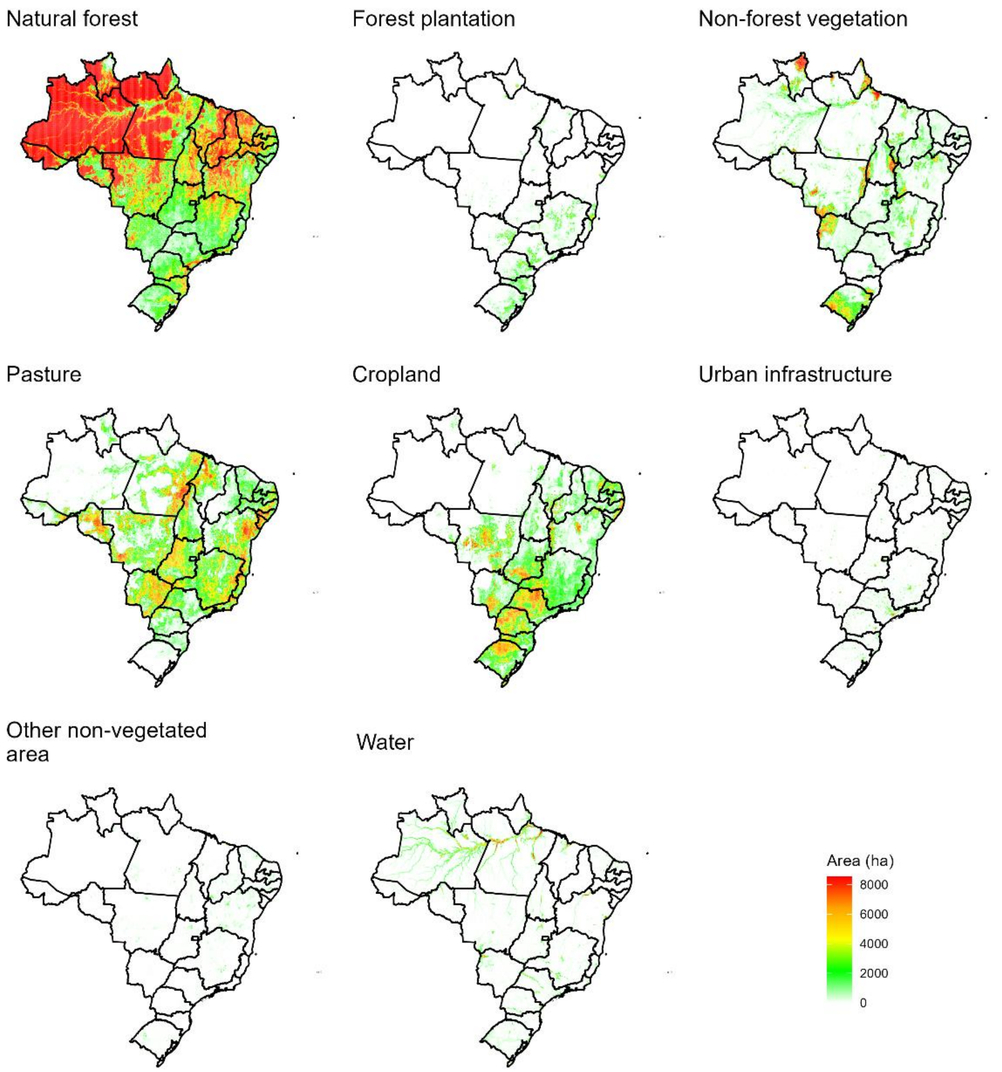
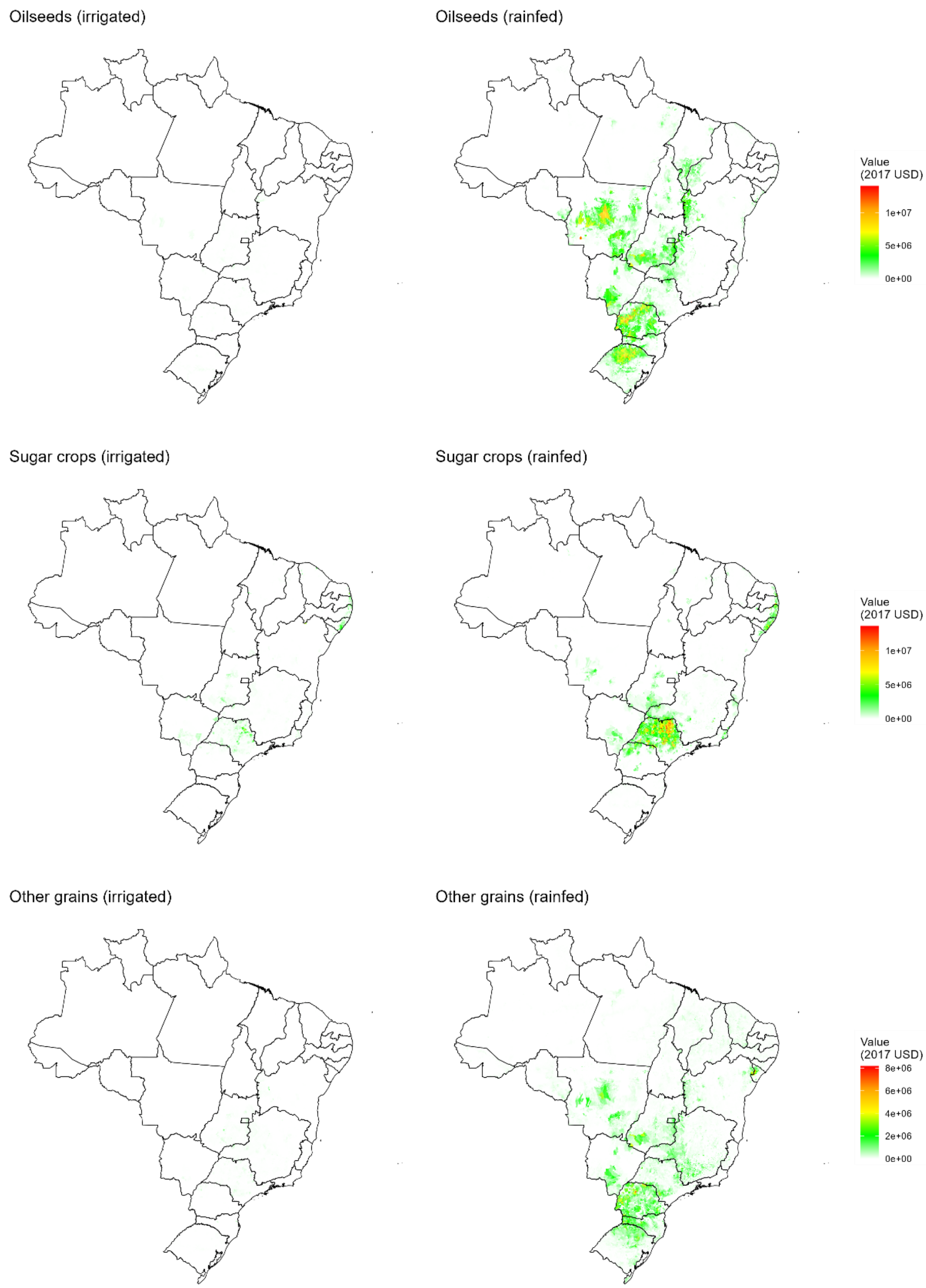
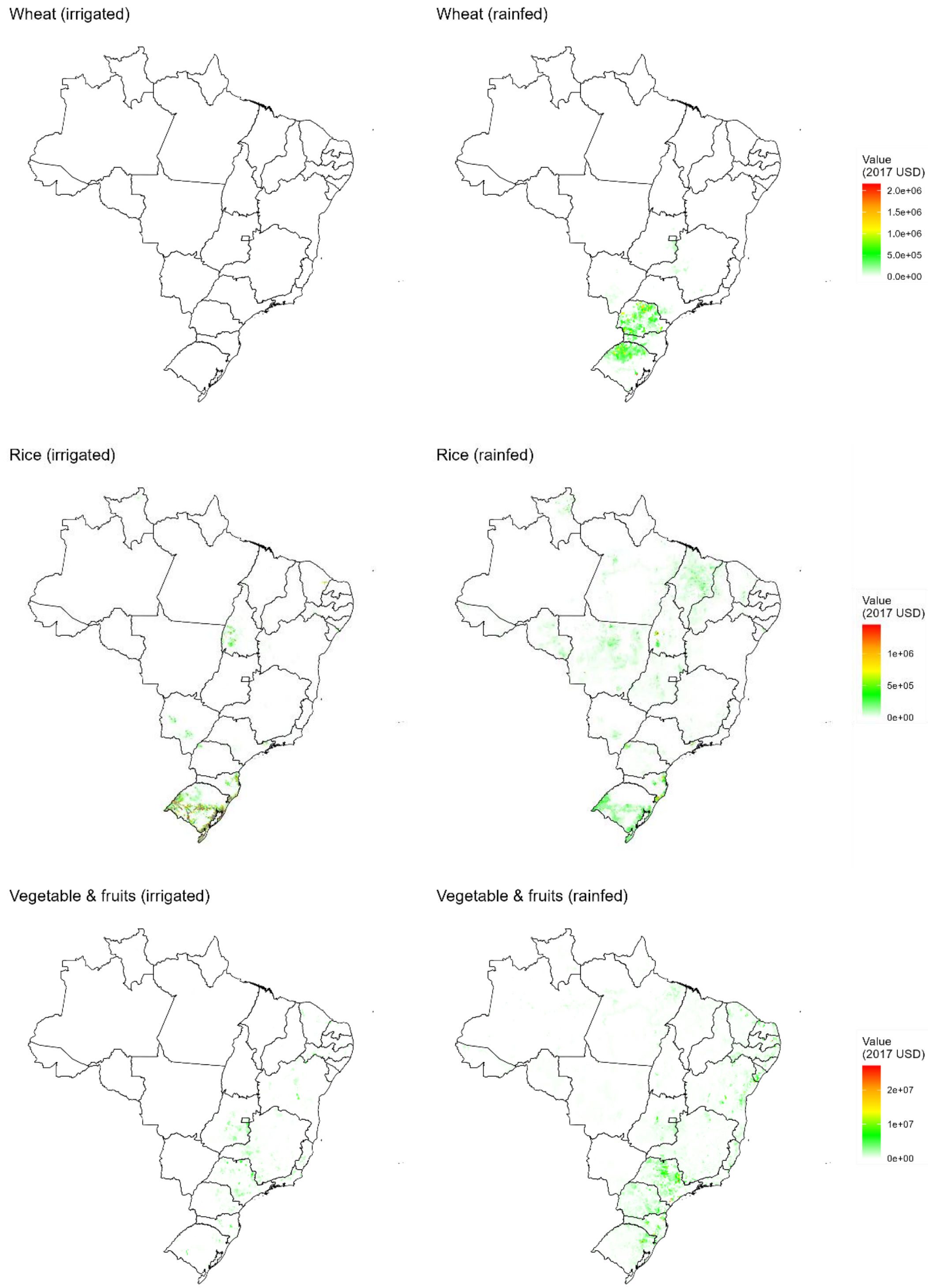


Figure D.1. Gridded land use area in 2017 baseline**.**

Notes: Black line represents state boundary.

Source: Author illustration.


Oilseeds (irrigated)
Oilseeds (rainfed)
Value
(2017 USD)
1e+07
5e+06
0e+00
Sugar crops (irrigated)
Sugar crops (rainfed)
Value
(2017 USD)
1e+07
5e+06
0e+00
Other grains (irrigated)
Other grains (rainfed)
Value
(2017 USD)
8e+06
6e+06
4e+06
2e+06
0e+00


Wheat (irrigated)
Wheat (rainfed)
Value
(2017 USD)
2.0e+06
1.5e+06
1.0e+06
5.0e+05
0.0e+00
Rice (irrigated)
Rice (rainfed)
Value
(2017 USD)
1e+06
5e+05
0e+00
Vegetable & fruits (irrigated)
Vegetable & fruits (rainfed)
Value
(2017 USD)
2e+07
1e+07
0e+00

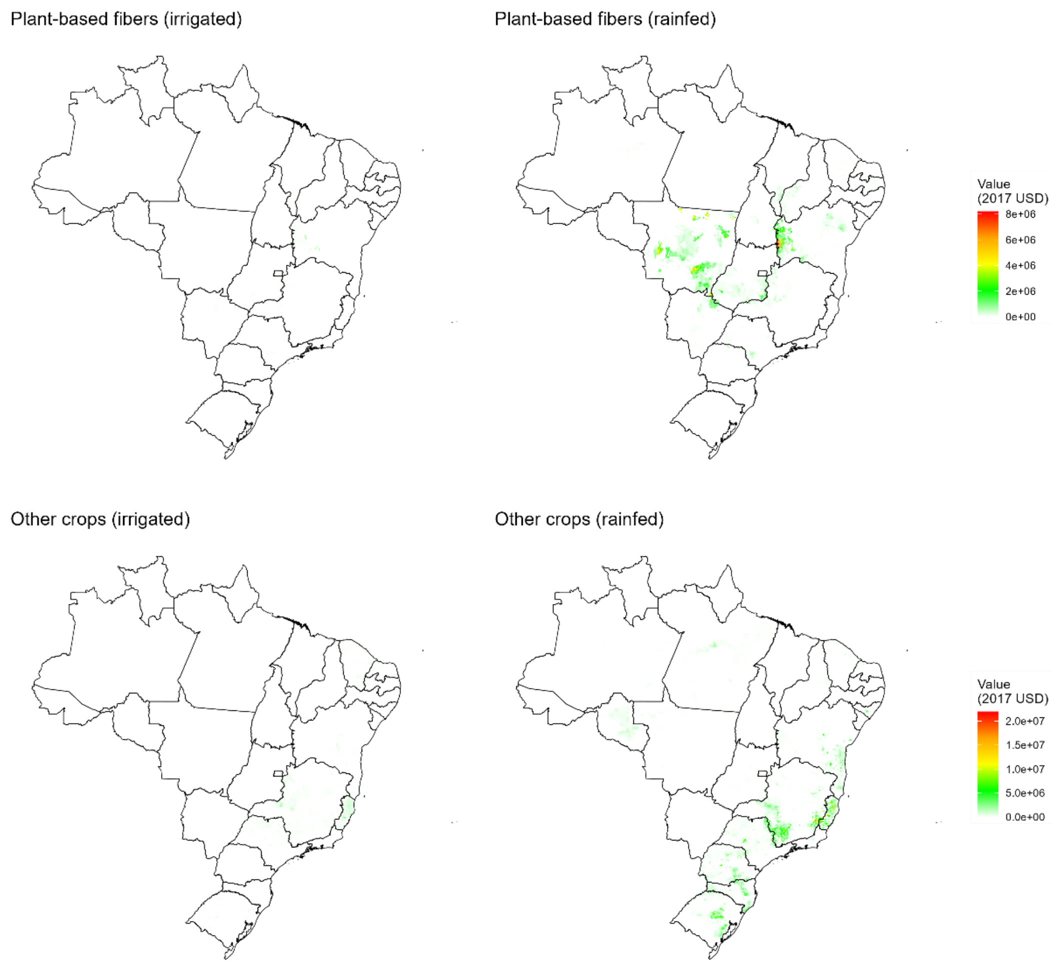


Figure D.2. Gridded crop output value in 2017 baseline.

Source: Author illustration.

Appendix E. Additional results

Table E.1. Change of land use and crop output at state and national level in Brazil.

State	Change in land use (1000 ha)			Change in crop output (1000 t)		
	Cropland	Pasture	Forest plantation	Oilseeds	Sugar crops	Other grains
Acre	0.00	0.00	0.00	0.00	0.00	0.00
Alagoas	-0.38	0.38	0.00	0.90	-837.68	-0.99
Amapá	0.01	-0.01	0.00	0.00	-0.05	-0.04
Amazonas	0.00	0.00	0.00	0.00	-4.23	-0.03
Bahia	2.28	-1.90	-0.38	91.96	-126.67	-20.55
Ceará	1.01	-1.01	0.00	5.96	-65.00	-21.09
Distrito Federal	0.81	-0.78	-0.03	12.90	-1.16	-6.08
Espírito Santo	-1.95	1.60	0.35	1.32	-143.27	-4.19
Goiás	45.44	-44.10	-1.34	319.35	216.48	172.33
Maranhão	2.11	-1.94	-0.17	90.64	5.27	0.11
Mato Grosso	51.78	-50.33	-1.44	1059.13	-38.19	275.23
Mato Grosso do Sul	31.75	-31.19	-0.56	276.92	-120.01	80.53
Minas Gerais	3.05	-3.05	0.00	121.51	-1041.90	-144.58
Pará	4.92	-4.78	-0.15	37.22	-11.65	-10.18
Paraíba	0.64	-0.64	0.00	0.26	-146.57	-1.30
Paraná	7.15	-0.67	-6.48	915.92	-984.88	-164.66
Pernambuco	1.17	-1.17	0.00	0.84	-574.84	-3.58
Piauí	0.34	-0.31	-0.02	67.48	-17.36	-9.28
Rio De Janeiro	1.20	-1.20	0.00	1.06	-149.02	-0.65
Rio Grande do Norte	0.70	-0.70	0.00	0.75	-118.31	-1.49
Rio Grande do Sul	8.05	-3.69	-4.36	681.52	-11.33	9.01
Rondônia	1.29	-1.29	-0.01	24.60	-5.43	-4.93

(Continued…)

Table E.1. Change of land use and crop output at state and national level in Brazil. (…Continued)

State	Change in land use (1000 ha)			Change in crop output (1000 t)		
	Cropland	Pasture	Forest plantation	Oilseeds	Sugar crops	Other grains
Roraima	0.07	-0.07	0.00	0.30	-0.03	-0.12
Santa Catarina	4.13	-2.10	-2.03	82.35	-16.89	-92.68
São Paulo	1.08	-0.83	-0.25	70.36	-11033.04	-113.08
Sergipe	0.29	-0.28	-0.01	4.88	-77.98	-30.25
Tocantins	8.12	-7.96	-0.16	62.54	8.37	9.52
Brazil	175.07	-158.04	-17.03	3930.65	-15295.38	-83.00

Source: Author calculations

Table E.2. Percentage changes (%) of national output of commodities in other regions (except the US, Brazil and China).

Commodity	Oceania	EastAsia	SEAsia	SouthAsia	NAmerica
Rice	0.05	0.02	0.01	0.01	-0.40
Wheat	-0.08	-0.11	-0.21	0.01	-0.51
OtherGrains	-0.05	-0.13	-0.01	0.00	-0.22
VegFruit	0.03	0.00	-0.01	0.00	-0.27
OilSeed	1.56	1.21	0.42	0.19	4.73
SugarCrops	0.23	0.09	0.18	0.31	0.05
PlantFibers	-0.13	-0.33	-0.52	-0.08	-0.27
OtherCrops	0.19	0.13	0.04	0.14	-0.10
Cattle	0.16	0.08	-0.03	0.11	-0.30
Forestry	-0.09	-0.02	-0.02	-0.01	-0.06

Commodity	LatinAmer	WestEurope	MENA	SSA	RestofWorld
Rice	-0.04	0.06	0.01	0.01	0.02
Wheat	-0.85	0.01	0.03	-0.19	-0.06
OtherGrains	-0.39	0.02	0.02	-0.01	-0.01
VegFruit	-0.21	0.06	0.02	-0.01	0.02
OilSeed	4.92	0.64	0.45	1.51	1.18
SugarCrops	0.11	0.25	0.59	0.16	0.40
PlantFibers	-0.48	-0.20	-0.12	-0.33	-0.12
OtherCrops	-0.35	0.29	0.22	0.04	0.16
Cattle	-0.01	0.07	0.09	0.04	0.07
Forestry	0.03	-0.01	-0.01	-0.03	-0.06

Source: Author calculations.