Science of the Total Environment 928 (2024) 172434

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Planned expansion of transportation infrastructure in Brazil has implications for the pattern of agricultural production and carbon emissions

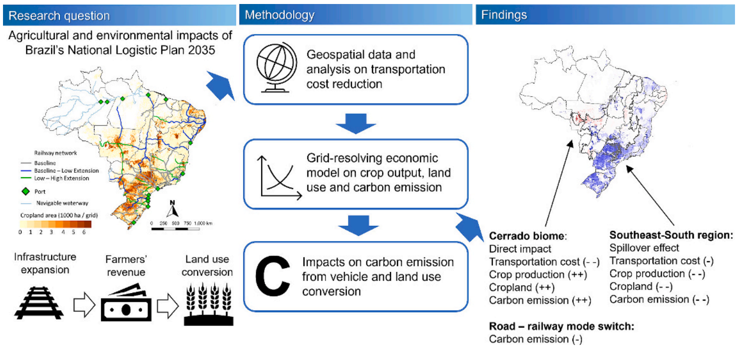
Zhan Wang [a,*], Geraldo B. Martha Jr. [b,c], Jing Liu [a], Cicero Z. Lima [d], Thomas W. Hertel [a]

[a] *Department of Agricultural Economics, Purdue University, 403 Mitch Daniels Blvd, West Lafayette, IN 47907, USA*
[b] *Embrapa Digital Agriculture, Dr. André Tosello, 209 - Cidade Universitária, Campinas, SP 13083-886, Brazil*
[c] *Graduate Program, Institute of Economics-CEA, Unicamp, R. Pitágoras, 353 - Cidade Universitária, Campinas, SP 13083-857, Brazil*
[d] *Sao Paulo School of Economics, R. Itapeva, 474 - Bela Vista, São Paulo, SP 01302-000, Brazil*

HIGHLIGHTS

- Brazil's logistic plan will expand railways by up to 90 %, its agricultural and environmental impacts remain under-addressed.
- We combine geospatial analysis for cost estimation and a grid-resolving economic model to analyze the impacts of this plan.
- This plan improves connectivity of the interior Cerrado biome, attracting crop production from Southeast-South regions.
- Increase of carbon emission in Cerrado can be offset by spillover effects to Southeast-South, depending on input mobility.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Kuishuang Feng

Keywords:
Transportation infrastructure
Agriculture
Land use
Carbon emission
Spillover effects

ABSTRACT

High transportation costs have been a barrier to the expansion of agriculture in the interior of Brazil. To reduce transportation costs, Brazil launched the National Logistics Plan, aiming to expand its railway network by up to 91 % by 2035. Such a large-scale infrastructure investment raises concerns about its economic and environmental consequences. By combining geospatial estimation of transportation cost with a grid-resolving, multi-scale economic model that bridges fine-scale crop production with its trade and demand from national and global perspectives, we explore impacts of transportation infrastructure expansion on agricultural production, land use changes, and carbon emissions both locally and nationally in Brazil. We find that globally, the impacts on output and land use changes are small. However, within Brazil, the plan's primary impacts are impressive. PNL2035 results in the reduction of transportation costs by 8–23 % across states (depending on expansion's extent) in the interior Cerrado biome. This results in cropland expansion and increases in terrestrial carbon emissions in the Cerrado region. However, the increase in terrestrial carbon emissions in the Cerrado is offset by spillover effects elsewhere in Brazil, as crop production shifts away from the Southeast-South regions and accompanying change

---

* Corresponding author.
E-mail addresses: zhanwang@purdue.edu (Z. Wang), geraldo.martha@embrapa.br (G.B. Martha), liu207@purdue.edu (J. Liu), cicero.lima@fgv.br (C.Z. Lima), hertel@purdue.edu (T.W. Hertel).

https://doi.org/10.1016/j.scitotenv.2024.172434
Received 17 November 2023; Received in revised form 16 February 2024; Accepted 10 April 2024
Available online 14 April 2024

in the mix of transportation mode for farm products from roadway to more emission-efficient railway. Furthermore, we argue that the transportation infrastructure's impact on the enhanced mobility of labor and other agricultural inputs would further accentuate the regional shift in agricultural production and contribute to carbon emission mitigation. Upon its completion, PNL2035 is expected to result in the reduction of net national emissions by 1.8–30.7 million metric ton of CO_2-equivalent, depending on the impacts on labor and purchased input mobility. We conclude that the omission of spillover effects due to infrastructure expansion can lead to misleading assessments of transport policies.

1. Introduction

Transportation infrastructure has been a widely recognized bottleneck limiting Brazil's agricultural potential and economic growth (Amann et al., 2016, 2018). Historically, rapid infrastructure development was undertaken with investments equivalent to 5.9 % of gross domestic product (GDP) over the 1947–1989 period. However, since that time, infrastructure investments have been declining, averaging 3.6 % of GDP in 1990–2015, and 2.3 % of GDP in 2016–2021 (Pires, 2022). Furthermore, land transportation in Brazil has been heavily dependent on the road network, while the railway network remains relatively underdeveloped. In 2017, the Brazilian roadway network (federal, state or municipal roadways) reached a length of 331,807 km, which stands in sharp contrast to only 21,286 km of railway lines (Ministry of Infrastructure, 2022). The United States is 1.09 times the size of Brazil, but its railway length exceeds 7 times the length in Brazil. Compared to Argentina, a country that is only 33 % of the size of Brazil, Brazil's railways are also underdeveloped, as Argentina's railway length is equivalent to 83 % of railway length in Brazil (World Bank, 2020). These comparisons indicate that Brazil has a yet to be developed railway network potential compared with its closest competitors in global agricultural trade.

While studies of Brazil's transportation infrastructure's impacts on environmental and land use have tended to focus on the Amazon biome (Viana et al., 2008; Barber et al., 2014; Santos et al., 2020), its agricultural impacts are particularly important in the Cerrado biome, due to this region's increasing importance in national and global crop production (Bicudo Da Silva et al., 2020; Souza et al., 2020; Valdes, 2022). The center-west region (a geographic proxy of the Cerrado biome[1]), accounts for the majority of the Cerrado's agricultural output. The center-west region dramatically increased its share in national grain production from 17.7 % in 1996 to 50.8 % in 2022 (Fig. 1). This growth is attributed to several significant agronomic advantages of Cerrado biome, including high yield potential (Marin et al., 2022), ample supplies of arable land, and the possibility of increasing the intensity of cultivation under rainfed conditions (i.e., cultivation of two or even three crops per year) (Vera-Diaz et al., 2008; Martha and Alves, 2018; Valdes, 2022). However, further growth has been constrained by high transportation costs (Gale et al., 2019). For example, the share of inland transportation cost in the Free on Board (FOB) port price for soybean exports (2018–2022 average) is 14–16 % in Mato Grosso (MT), a much higher figure than in the domestic competing regions (6 %) from Rio Grande do Sul (RS) in south Brazil (Salin, 2023). High transportation costs in the Cerrado lower profit margins, curb agricultural growth, and potentially undermine export competitiveness of crops (Tiller and Thill, 2017; Valdes, 2022).

To address concerns about these logistics costs, in 2021 Brazil launched the 2035 National Logistics Plan (PNL2035), a large-scale infrastructure expansion plan that aims to achieve a major expansion of the railway network by 2035 (Fig. 2). According to PNL2035, if ongoing infrastructure projects are completed (the low improvement scenario, which is referred to as scenario “low” henceforth), the railway length is expected to increase by 59 % relative to 2017. In addition to the connection with ports in the North (São Luís, MA), this scenario will particularly improve the connectivity of the MATOPIBA[2] regions with ports in the Northeast (Salvador, BA) and Southeast (Santos, SP) regions with a North-South railway corridor. Under the most ambitious scenario, which involves completing all planned infrastructure expansion (the high improvement scenario, or scenario “high” henceforth), the total railway length will be increased by 91 % compared to the 2017 baseline. This scenario, among other features, introduces another corridor that will connect Mato Grosso (MT) state with the North-South railway and from there to ports in both the North and Southeast regions. The impact of PNL2035 on roadway length is negligible (<1 %). As a result, if PNL2035 is fully implemented, there will be a significant shift of commodity transportation mode from roadways to the more cost-effective and environmentally efficient railways. It also translates into a substantial increase in the connectivity between the Center-west region to urban centers on coastal regions and international markets. Both effects would contribute to the reduction of transportation costs, increasing farmers' revenue and boosting agricultural potential in Brazil.

Despite the anticipated economic benefits, the PNL2035 raises concerns about the potential negative environmental externalities associated with transportation infrastructure expansion, both directly and indirectly. Infrastructure plans can cause direct disturbance of natural habitat, causing native vegetation and biodiversity loss. For example, Brazil's Supreme Court is now hearing the case of “Ferrogrão”, a 933 km railway between Sinop (Mato Grosso, MT) and Miritituba (Pará, PA), to be built along the federal highway BR-163. Current scrutiny revolves around the way that the demarcation of Jamanxim National Park, in Pará, was changed to allow 53 km of the railway to cross the Park. This railway will have an estimated direct impact of 0.8 thousand hectares (ha) of land (Rossi and Alfinito, 2023) out of a total Park area of around 863 thousand ha (the Ministry of Environment and Climate Change, n. d.).

Infrastructure plans can also increase pressures on the environment indirectly through market channels leading to increased crop production. Enhancing the connectedness of agricultural regions to global markets decreases the cost of moving inputs (fertilizer, labor, capital, etc.) to the farm, as well as the cost of transporting crops to markets. This “double dividend” from reduced transportation costs will boost land returns (Fliehr et al., 2019) and labor mobility (Lucich et al., 2015), thereby encouraging cropland expansion (Schielein et al., 2021). In the presence of ineffective monitoring, control, and enforcement of environmental regulations, further pressures on the environment may occur, including deforestation, land conversion and carbon emissions (Reid and De Sousa, 2005; Thomas, 2006; Laurance et al., 2015; Assunção et al., 2020; de Barros and Baggio, 2021; Araujo et al., 2023). These prior findings suggest the transportation network expansion from PNL2035 is likely to bring economic and social benefits, given an increased agricultural production, at the expense of the environment.

---

[1] The Center-West region of Brazil consists of the federal district (Distrito Federal, DF) and three states: Goiás (GO), Mato Grosso (MT) and Mato Grosso do Sul (MS). The Cerrado biome overlaps with the majority of Center-West region, but also contains parts of Maranhão (MA), Tocantins (TO), Piauí (PI) and Bahia (BA). For the exact geographic boundary of biomes, please refer to Fig. A. 1 in supplementary materials.

[2] MATOPIBA refers to four states located in Northeast Cerrado biome: Maranhão (MA), Tocantins (TO), Piauí (PI) and Bahia (BA).

This could be a trade-off case of two goals of sustainability - gains in socioeconomic dimensions with losses in the environmental dimensions. Still, the potential agricultural and environmental impacts of such large-scale infrastructure expansion plan have not received sufficient attention.

In this study we explore the inter-related effects of planned infrastructure in Brazil on the change in cargo transport cost, the ensuing impact on agricultural production, and consequences for land use change and carbon emissions, both locally and across Brazil. To accomplish this, our study quantifies PNL2035's impacts on location-specific monetary transportation costs of crops with geospatial data on infrastructure, land use and geography. We further incorporate this information into SIMPLE-G-Brazil, an economic model developed by the authors that resolves the effect of PNL2035 on crop production, land use and carbon mission at the grid level. This allows us to capture the spatial heterogeneity in farming as well as the spillover effects across regions, aggregating these impacts to the national level to satisfy the supply-demand equilibrium for crops, both domestically and in international markets. As the estimated impacts of PNL2035 on agricultural labor and capital mobility have not previously been quantified, we employ a bounding analysis wherein we explore two polar extreme scenarios of farm input mobility: full factor mobility and no mobility across grids. This allows us to highlight the sensitivity of our findings to input mobility. Findings of this study extend the existing literature on transportation infrastructure's agricultural and environmental effects, as well as drawing out implications for policy makers.

2. Literature and gaps

The socio-economic impacts of transportation infrastructure have been well addressed in the literature, including the effect on interregional pricing (Donaldson, 2018) poverty alleviation (Aggarwal, 2018), labor markets (Asher and Novosad, 2020), regional development (Bottasso et al., 2021), cropland expansion and deforestation (Santos et al., 2020). Focusing on the environmental aspects, the extension of transportation infrastructure can affect natural vegetation ecosystems and habitats, by enhancing human access for timber, agricultural cultivation, mining and hunting activities. These ecosystem alterations affect the habitats and migration corridors for wild species, as well as resulting in environmental degradation from soil erosion, stream sedimentation and pollution from vehicles (Laurance et al., 2009). The improved connectivity through transportation infrastructure will not only strengthen the direct disturbances in the environment, but will also cause indirect impacts by increasing farmers' profitability, enhancing agricultural production and land conversion (Fearnside, 2008; Asher et al., 2020).

While many studies of transportation infrastructure's economic and environmental impacts have now been undertaken as mentioned above, several important knowledge gaps remain. First, most of the existing studies in Brazil are retrospective and focus on the historical construction of transportation infrastructure (Frohn et al., 1990; Pfaff, 1999; Ferraz, 2001; Thomas, 2006; Rodrigues-Filho et al., 2012; Escobar et al., 2020). Results from those studies mainly reflect impacts stemming from the road-dependent transportation network, while studies on the planned large-scale expansion of railway network from PNL2035 are still at an early stage.

In addition, most existing studies focus on the particular region where infrastructure construction takes place (Pedlowski et al., 1997; Weinhold and Reis, 2008; Barber et al., 2014; das Neves et al., 2021), but the impacts of transportation infrastructure investments are not locally restricted. When infrastructure improves connectivity in one region, it increases the comparative advantages of farming, relative to other regions. These effects will be transmitted to other regions through national product markets, thereby influencing crop output and cropland expansion dynamics and causing potential spillovers to other regions. For example, Cattaneo (2008) found that increasing agricultural opportunities outside the Amazon biome reduces the incentives of land cultivation in the Amazon. The impacts on geographically separated but market-connected regions, is usually discussed as spillover effects or leakage effects (Yang et al., 2019; Meyfroidt et al., 2020). However, these effects have yet to be sufficiently addressed in existing literature on transportation infrastructure.

To understand the impacts of planned infrastructure expansion, one major challenge is to quantify the relationship between infrastructure and transportation cost at a fine spatial scale. Existing infrastructure studies have assessed the impacts of new transportation routes on

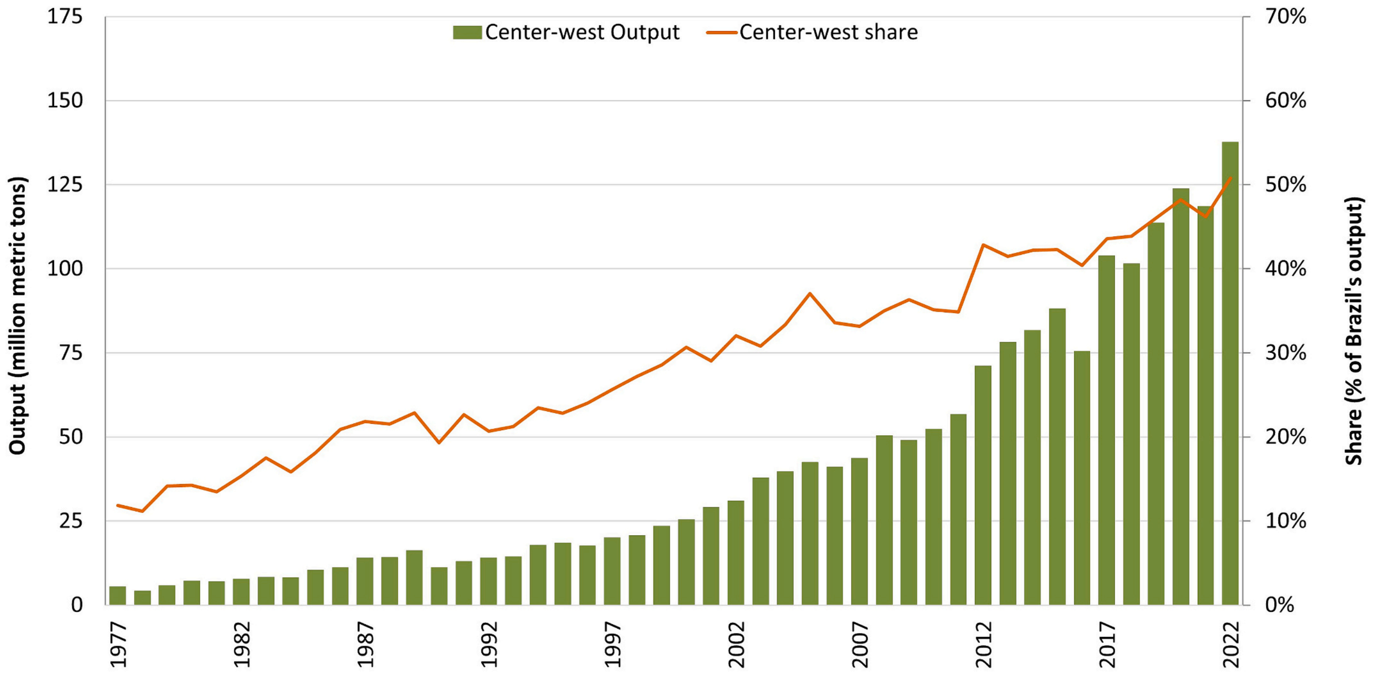


Fig. 1. Evolution of grain (soybean, corn, rice, and cotton) output in Brazil's Center-west, 1977–2022. Data source: National Supply Company (Conab), Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA).

Brazil's agricultural commodity production and exports using gravity models (da Silva and de Almeida D'Agosto, 2013), linear programming supported by origin-destination matrices (de Oliveira et al., 2021), and principal component and clustering analysis (de Oliveira et al., 2022). While this literature provides useful insights into the infrastructure's impact in Brazil, they focus on the state or sub-state level, while the transportation cost at a finer spatial scale remains outside of their research scope. Applying the least-cost (traveling time) path algorithm, Weiss et al. (2018) construct a global map of gridded accessibility to cities, which can be regarded as a proxy of transportation cost. Fontanilla-Diaz (2021) further takes the road condition and labor use by transportation mode into consideration to calculate access costs measured in person-hours for two states in Brazil. To our knowledge, Costa et al. (2022) is the only study that assesses the transportation cost reduction due to PNL2035 in monetary terms. Those authors combine the least-cost algorithm and transportation cost per distance data to calculate transportation cost to ports at a gridded level. They find that the planned railway expansion would improve the connectivity between Brazil's Center-west region with coastal regions in the Southeast-South and that would reshape port competitiveness in the country. However, their study does not address the associated agricultural and environmental impacts. In addition, the impacts of PNL2035 on the accessibility of agricultural inputs have not been evaluated in prior work. Despite infrastructure's key role in meeting the Sustainable Development Goals (SDGs) (Economist Intelligence Unit, 2019), these remain significant knowledge gaps still need to be addressed, in particular from a local – regional – national perspective.

3. Methods

3.1. Transportation cost: measurement, calculation and validation

Transportation cost in this paper is defined as the lowest expense of transporting one metric ton of crop from each production grid to the destination of final demand. In order to balance the computational burden and the spatial granularity of analysis, instead of estimating transportation cost for all 50,598 five-arcmin grids (the spatial resolution for SIMPLE-G-Brazil model), we estimate these costs for 558 micro-regions.[3] These are used to represent the transportation cost faced by all grids located within that micro-region. The centroid of each micro-region is selected as the origin of all routes. Following Victoria et al. (2021), we selected export ports as destinations for crop transportation,

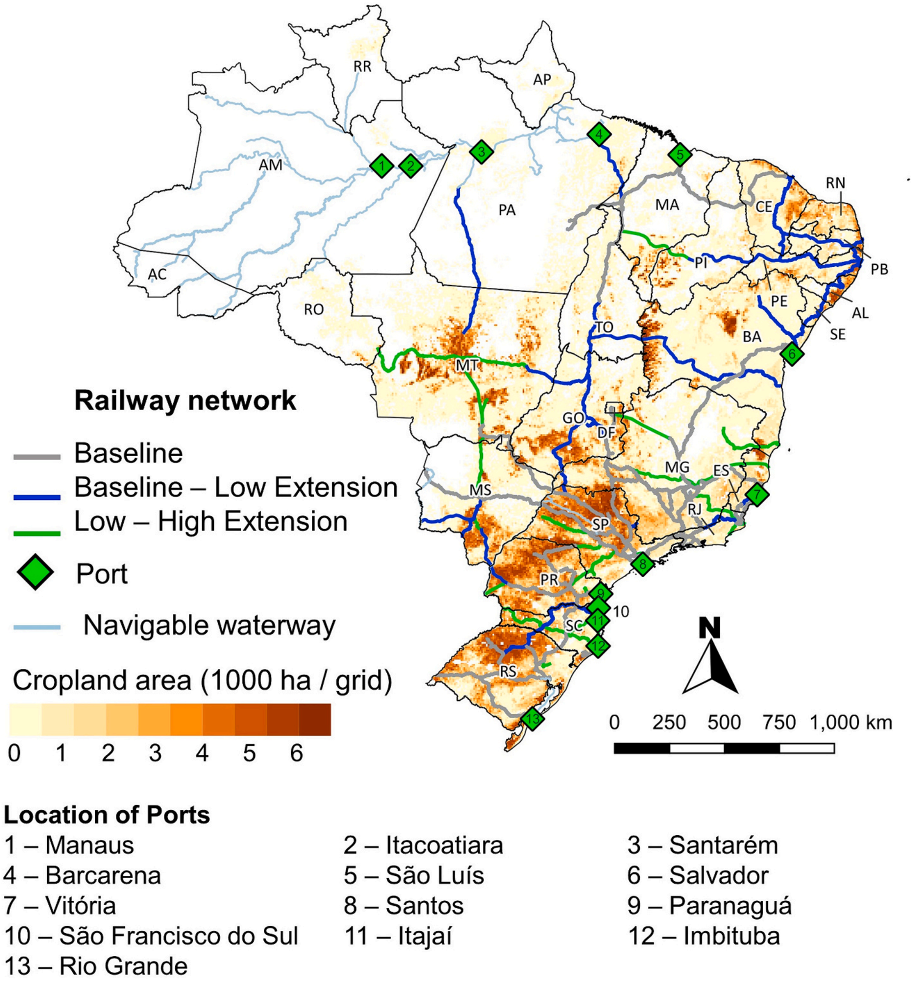


Fig. 2. The railway network in 2017 baseline (gray line), and the planned expansions under PNL2035 from baseline to scenario low (blue line), and from scenario low to scenario high (green line) (Ministry of Infrastructure, 2022). For reference purpose, Fig. 2 also shows the cropland area per 5-arcminute gridded level (MapBiomas, 2020), locations of crop export ports at municipality level (Victoria et al., 2021) and the navigable water way network (Ministry of Infrastructure, 2022) at baseline, as well as abbreviations of state names (a list of states' full names is available in Table A.1 in supplementary materials).

---

[3] The regional division of Brazil consists of States and Municipalities (level of administrative divisions). In this study we used Microregions, sets of contiguous municipalities, which are equivalent to the county level in the United States. The entire Brazil consists of 558 micro-regions.

because exporting constitutes the majority of final demand for Brazilian feed crops, e.g., 58 % of total corn and soybean outputs (Lopes, 2021). Also, those ports are located in the most densely populated regions (IBGE, n.d., p. 2010) which coincide with the bulk of domestic consumption.

The estimation of the least transportation cost for a certain origin to any destination is conducted with two steps. In the first step, we build a raster data base of friction surface at the 30 arc-second pixel[4] level. This database records the inconvenience of transporting as the inverse of speed (i.e., minutes required to travel 1 m), with the shapefile of infrastructure network (Ministry of Infrastructure, 2022), and the raster data of land cover (Friedl and Sulla-Menashe, 2019) and elevation (Danielson and Gesch, 2011). If a pixel is located on the road network, we assigned the average speed from paved and non-paved road from Schielein et al. (2021) (due to the unavailability of road type and status from the network shapefile). If a pixel is located on the railway network, we used the ratio of transportation cost rate ($/km) between road and railway from ONTL (2022) to adjust the speed of road transportation and assign it to the pixel on railway (due to the unavailability of railway speed data by route). We recognize that this adjustment does not result in a rigorous measurement of transportation speed for railway transport. Instead, we use it to represent the preference of railway over road way due to the lower transportation cost rate, when both networks are available. If a pixel is not located on a road or railway network, we assign a speed based on the land cover type it belongs to, and adjust that base speed for elevation and slope (calculated from elevation raster) following Weiss et al. (2018). The calculation of the transportation speed raster and the corresponding transportation friction surface is conducted with QGIS (version 3.16), a widely used free and open-source software for geographic information system analysis. We then used the "Least cost path" plugin (FlowMap Group, 2022) available in QGIS to identify the path with the least accumulated friction between the origin and all thirteen ports. This approach allows us to identify an optimal route (in term of the shortest transportation time) between each origin – destination pair from numerous possible routes on the map, it also considers both on-road/rail and off-road/rail transportation, regardless with the proximity of origins to existing transportation networks. It remains to determine the least cost destination, among the 13 routes (to the 13 ports).

To that end, in the second step we first overlay each route with the PNL2035 projected transport network to distinguish the segments that overlap with the railway network (to identify rail transport distance) from those that do not (to identify road transport distance). Next, distance is converted to transportation cost via the rate for transporting agricultural commodities by railway or road (Brazilian Reals per metric ton, R$/t, later converted to USD/metric ton, $/t, based on 2017 USD) provided by the National Observatory of Transport and Logistics (ONTL, 2022).[5] Finally, the route with the lowest total expense (railway and road combined) is selected as the favored transportation destination for each micro-region. And the corresponding expense becomes the transportation cost for that micro-region. This is applied to all grids within that micro-region for the purposes of analysis within SIMPLE-G-Brazil.

We validated our method against reported transportation data from the National Supply Company (Conab) under the Ministry of Agriculture, Livestock and Food Supply (CONAB, 2022). The database of Conab contains the information of route origin and destination, distance and transportation cost[6] for 925 unique routes since 2014. We use the origin and destination information to calculate the total transportation distance and cost as described above, then test the closeness of the calculated and reported data with a linear regression model ($y = \alpha + \beta x$. y: reported distance/cost; x: calculated distance/cost). The linear regression model performs very well: $R^2 = 0.879$, coefficient $= 0.908$ for distance and $R^2 = 0.810$, coefficient $= 1.064$ for cost. Both coefficients are significant at the $p = 0.01$ level. These results indicate that the transportation distance and cost calculated with our method closely match observed data. Finally, we calibrate a port-specific adjustment scalar by comparing the estimated and observed share of crop transported by port, in order to capture unobserved factors that influence the choice of transportation destination besides transportation cost.

With this validated transport network framework in hand, we apply this method to calculate transportation cost at a spatial level for the baseline as well as for the two investment scenarios (low and high), to obtain PNL2035's effect on transportation cost reduction at the level of individual production grid cells. These transport cost changes serve as external shocks to the model, allowing us to simulate their impacts on land use, agriculture production and carbon emissions. Additional details about the method and its validation are provided in supplementary material A.2.

3.2. SIMPLE-G-Brazil: a multiscale model for agricultural and environmental impact assessment

To analyze PNL2035's agricultural and environmental impacts, we implement the transportation cost reduction from the various scenarios in a grid-resolving economic model: the Simplified International Model of agricultural Prices, Land use and the Environment: Gridded version for Brazil (SIMPLE-G-Brazil), which is developed by authors of this study following the non-gridded SIMPLE model (Baldos and Hertel, 2012; Hertel and Baldos, 2016; Lima et al., 2022) and several versions of gridded SIMPLE models for other regions (Liu et al., 2017; Baldos et al., 2020; Haqiqi et al., 2023a, 2023b; Ray et al., 2023).

SIMPLE-G-Brazil belongs to the category of partial equilibrium models, and its key equations are derived from a theoretical model based on fundamental economic assumptions (consumers select commodities to maximize utility, producers select inputs to produce commodities and minimize cost, price adjusts so that the supply of commodities satisfies demand). In contrast to econometric methods (see Kasraian et al. (2016) for a comprehensive review on transportation infrastructure), the partial equilibrium approach allows us to explicitly model the relationship between inter-connected components (supply, trade, demand) within the economy, which is necessary to capture the multiple-tier causality from transportation network expansion to crop production, land use and carbon emission in this study. Our approach is also distinct from studies using computable general equilibrium models that seek to capture the economy-wide response from all sectors and resolve at the national or sub-national level, for example the regional TERM-BR model (Silva et al., 2017) and the global GTAP-BIO model (Zhao et al., 2021). Our partial equilibrium approach abstracts from the non-agricultural sectors in order to permit higher resolution (at the grid level) of agricultural activity and the associated environmental impacts.

Within the category of partial equilibrium models, SIMPLE-G-Brazil shares the grid-resolving feature with the GLOBIOM model (Havlík et al., 2011) and its regional variant GLOBIOM-Brazil model (Zilli et al., 2020), but differs from them in multiple aspects. Models from the GLOBIOM family focus on the finer classification of commodities within the agricultural sector and the dynamic process of simulation at the (much coarser) resolution of 250,000 ha per grid. Furthermore,

---

[4] The pixel of 30 arc-second resolution is selected because it matches the resolution of elevation data and is close to the resolution of land use data (500 m). In this study, pixels are only used to construct the friction surface for the optimal route identification, while all other grid level simulation and visualization are based on five-arcmin grids.

[5] ONTL only provides the relationship between transportation distance (km) and cost (R$/t), without further information on road type, status, pavement or the marginal cost with quantity.

[6] The Conab data provide the transportation distance and cost for a certain route (pair of origin and destination), but without the mode-specific information. So we treated it as the total transportation cost.

domestic transportation cost is modeled at national or more aggregated level. On the other hand, SIMPLE-G-Brazil focuses on the change between two equilibrium states at a much finer spatial resolution (<10,000 ha per grid). It also allows the transportation cost to be spatially explicitly modeled at the grid level. These are both important features for understanding the spatial impacts of transportation infrastructure expansion. SIMPLE-G-Brazil is also distinct from the partial equilibrium models in the non-gridded, SIMPLE family. The SIMPLE model simulates responses only at the global and regional (national or more aggregated) levels. Compared with other gridded SIMPLE models, the development of SIMPLE-G-Brazil is based on Brazilian official data sources, and its model structure has been updated to incorporate transportation cost's impact on farm-gate crop price for the purpose of this study.

SIMPLE-G-Brazil simulates gridded equilibrium quantities and prices for crop output and inputs (fertilizer, cropland, labor and capital, irrigation water and equipment) in response to exogenous socio-economic drivers and policy shocks (Fig. 3). It divides the world economy into 17 regions and further disaggregates the region “Brazil” into 50,598 five arc-minute grid cells[7] (the area of each grid cell is roughly 7750–8550 ha in the Cerrado region). Each grid distinguishes rainfed and irrigated crop production, and each of these activities exhibits distinct input intensities and yields.

In SIMPLE-G-Brazil, transportation cost is modeled as an exogenous price wedge between two endogenously solved crop prices: the international, free-on-board (FOB) price at the port, and the grid-specific farm-gate price (Eq. (1)):

$$P^{FOB} = P_i^{FG} + P_i^{TC} \tag{1}$$

In this model, we assume all grids in Brazil faces the same FOB price (P^{FOB}). In grid i, the reduction in transportation cost (P_i^{TC}) increases the farm-gate price (P_i^{FG}) and therefore the profit margin, leading farmers to expand cropland area and increase the use of inputs, potentially adding additional harvests as well.

The behavior of farmers is modeled with the assumption that farmers select the usage of cropland (extensive margin) and non-land inputs (intensive margin) to minimize the cost for producing a certain unit of crops.[8] Following existing literature on economic modeling (Hertel and Baldos, 2016; Silva et al., 2017; Zhao et al., 2021), we assume the production functions (crop output as a function of land and non-land inputs) follow a bottom-up and nested constant elasticity of substitution (CES) functional form that allows substitution between inputs in response to changing relative prices. The behavior of a farmer in grid i can be represented by Eq. (2):

$$\begin{gathered} \min_{L_i, NL_i} r_i L_i + w_i NL_i, \text{ subject to :} \\ \alpha_i \left(\delta_L L_i^{\frac{\sigma-1}{\sigma}} + \delta_{NL} NL_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \geq Q_i \\ r_i L_i + w_i NL_i \leq P_i^{FG} Q_i \end{gathered} \tag{2}$$

where L_i, NL_i refer to the usage of cropland and non-land inputs, r_i and w_i refer to the land rent and non-land input price respectively, Q_i refers to the level of crop production, α, δ and σ refer, respectively, to the CES function's productivity parameter (representing the overall productivity of farming), share parameter (representing benchmark value of inputs share) and substitution elasticity (representing the potential for substitution between inputs in production technology). The production function is inelastic in substitution when $0 < \sigma < 1$, and is elastic when $\sigma > 1$. The first condition in Eq. (2) indicates that the production from the CES function must satisfy the demand of crop production in that grid (Q_i), while the second conduction requires that the total cost of farming cannot exceed the total revenue of selling crops, otherwise the farmer go out of business.

For purposes of analysis and interpretation, we can linearize the solution to (2), yielding the following change in cropland demand equation (the demand for the non-land input has a similar form):

$$\widehat{L_i} = \widehat{Q_i} + \sigma\left(\widehat{\delta_L} + \widehat{P_i^{FG}} - \widehat{r_i}\right) + (\sigma - 1)\widehat{\alpha_i} \tag{3}$$

Eq. (3) provides a series of important implications from our model. It indicates that the change of cropland area comes from three components: the scale effect $\widehat{Q_i}$, the substitution effect $\sigma\left(\widehat{\delta_L} + \widehat{P_i^{FG}} - \widehat{r_i}\right)$, and the productivity effect $(\sigma - 1)\widehat{\alpha_i}$. When the expansion of transportation infrastructure benefits a certain region more than other regions, the national agricultural pattern will shift to that region from the rest of Brazil, causing the increase of cropland demand in that region and the decline of cropland demand in other regions via the scale effect. However, the magnitude of cropland expansion in response to infrastructure expansion also depends on the feasibility to substitute non-land inputs with cropland in crop production. If the feasibility of substitution is limited (low value of σ) or very costly (high value of $\widehat{r_i}$) due to the limited cultivation potential or unfavorable agricultural conditions, the substitution effect predicts the expansion of cropland would be hindered. Finally, the productivity effect relates to the impact of technological improvements on land use. When the production function is elastic in substitution ($\sigma > 1$), the increase of productivity encourages farmers to increase their cropland use for higher revenue. While when the function is inelastic ($0 < \sigma < 1$), that productivity increase reduces the amount of land demanded for a given output level.

Eqs. (1)–(3) depict the relationship between transportation cost, the extensive margin (cropland expansion) and the intensive margin (yield increase) of crop production for a single grid. But the individual grids are further connected with other grids via changes in output and input prices. And the local responses from all grids are further aggregated to the level of domestic and global markets wherein supply-demand equilibrium must be obtained. This equilibrium determines the FOB price, which is endogenous to the model. The spatially detailed production system enables the model to capture local responses (e.g., crop production and inputs use) to large-scale perturbations with spatial heterogeneity (e.g., reductions in transportation cost), as well as spillover effects across grids and regions via market linkages.

Besides the economic mechanisms described above; we also incorporate restrictions on cropland expansion from the Brazilian conservation policy into this model. The native vegetation protection law in Brazil requires that a certain share of land to be set aside and cannot be cultivated by landowners, in order to conserve native vegetation (Metzger et al., 2019). To reflect this policy's impact, we restrict the land supply elasticity (this elasticity governs the expansion of cropland in response to higher land rent) to be zero if the current cropland occupation has reached constraints provided by the native vegetation protection law.

The development of SIMPLE-G-Brazil encompasses a diverse range of datasets that provide detailed information on Brazilian agriculture, benchmarked at the baseline of 2017. At the grid level, we collected cropland area from MapBiomas (2020). We also collected yield data from Portmann et al. (2010) and adjusted them with micro-region level data from the Brazilian Institute of Geography and Statistics (IBGE) (Prado Siqueira, 2022) to the baseline. Also, we used the municipality-level irrigation ratios from the IBGE (2019) agricultural census to calculate the share of irrigated cropland at grid level. At the national level, we collected cropland area, output, and price from FAOSTAT

---

[7] The five-arcminute resolution of grid is selected to match the most of gridded agricultural data used in model development.

[8] For the convenience of introducing model structure here, in the manuscript we provide a simplified example of production function, which only contains one nest of two inputs (land and non-land). The SIMPLE-G-Brazil models uses a multi-nest structure of production function with five inputs, but the economic theory behind functional forms remains the same. Please refer to supplementary materials A3.1 for detailed information on key equations of SIMPLE-G-Brazil.

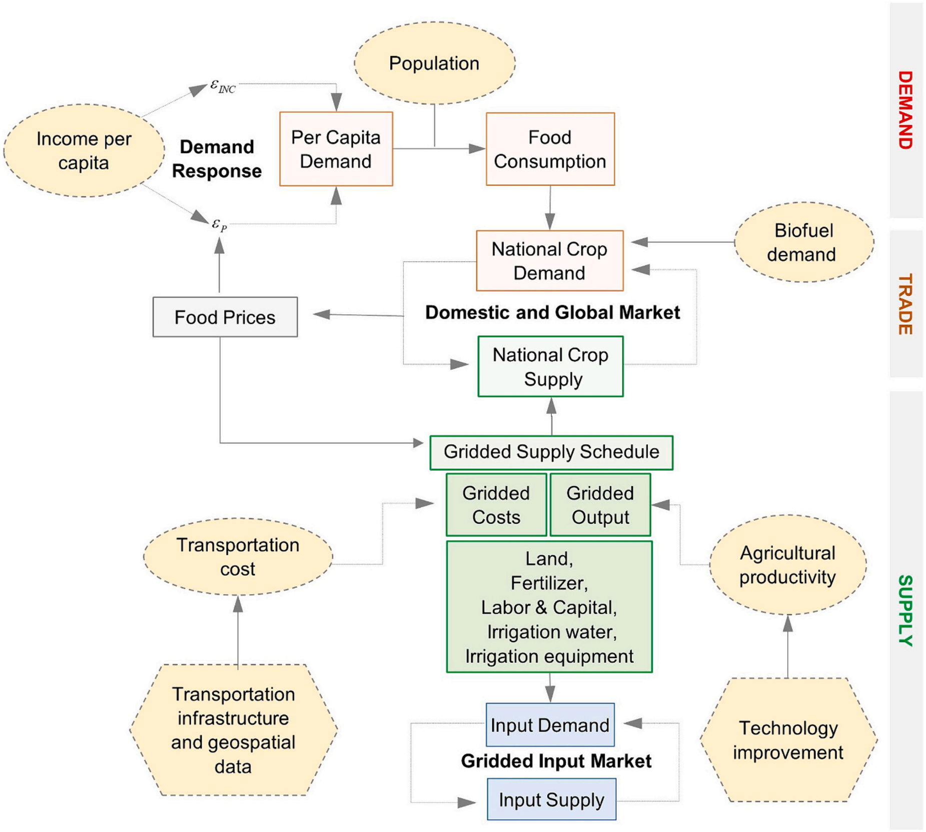


Fig. 3. Overview of the SIMPLE-G-Brazil model with transportation module, modified from Fig. 1 in Haqiqi et al. (2023a).

(FAO, 2021), population and per capita gross domestic product from the World Bank open data (World Bank, 2020), crop demand by direct consumption and sectors from the Global Trade Analysis Project database (version 10) (Aguiar et al., 2019), and other data for non-Brazil regions from the standard SIMPLE model (Hertel and Baldos, 2016). We aggregated output of all crops to "corn-equivalent" metric tons following the price weighting aggregation approach in Hayami and Ruttan (1985). For long run analyses where crop prices tend to move together, this is a valid approach and it circumvents the challenge of collecting crop-specific data at grid level and the complexity of specifying dozens of cross elasticities of demand and supply between disaggregated crops. This comprehensive collection of data sources provides an up-to-date database that represents the multi-scale features of the Brazilian agricultural system.

SIMPLE-G-Brazil has been validated with historical observations on crop output and cropland during 2000 to 2017. Hertel and Baldos (2016) validated the original non-gridded SIMPLE model over the period 1961–2006, but the results showed that the performance of the model needed to be improved for Latin America. Lima et al. (2022) made significant progress on this front by validating a specialized version of the non-gridded SIMPLE in which Brazil was broken out as an individual region. In this study, we hindcast SIMPLE-G-Brazil from its 2017 baseline back to 2000 with historical changes in socio-economic drivers (population, per capita GDP, productivity and biofuel) and global crop price. Results show that this model can reproduce historical cropland use and crop production reasonably well. Simulations were conducted using the GEMPACK economic modeling software (version 12) (Horridge et al., 2018). Additional information about SIMPLE-G-Brazil, including model structure, data source, model validation and calibration is available in supplementary material A.3.

3.3. Experiment design

We quantify the impacts of the transportation infrastructure improvements by simulating SIMPLE-G-Brazil with three different infrastructure scenarios for the year 2035. All scenarios include the same regional macro-level drivers, including projected changes in population (KC and Lutz, 2017), GDP per capita (Dellink et al., 2017), crop demand for biofuels (OECD and Food and Agriculture Organization of the United Nations, 2020), and total factor productivity (TFP) projections for crops (Fuglie, 2022), livestock (Ludena et al., 2007), and processed food (Griffith et al., 2004). The only difference between these scenarios is the perturbation introduced by the improved transportation infrastructure. In the *business-as-usual scenario* "*BAU*", we assume that PNL2035 is not implemented and the transportation cost in 2035 remains at the 2017 level. This serves as a baseline for evaluating impacts of infrastructure improvements. Two policy scenarios are considered: *scenario* "*Low*" assumes only the infrastructure projects already in progress would be completed, and *scenario* "*High*" assumes all planned infrastructure expansion would be completed by 2035. For ease of interpretation, we present the difference between "BAU" and "High" scenarios as main results (except in Fig. 4). Additional results for scenario "Low" are available in supplementary material A.6.

The impacts of infrastructure expansion on carbon emissions are captured through two distinct channels: changes in terrestrial carbon stock due to land use conversion, and transport-related emissions. The changes in carbon emissions from transport were estimated using the transportation emission factors (40 for railway and 150 for road, measured as CO_2-equivalent grams emitted per metric ton of crops per km) from the middle of value range reported in Sims et al. (2014). Terrestrial carbon emissions from land use change were estimated based on simulated cropland area change, together with carbon stock factors by land use type (Novaes et al., 2017) and tillage status (Fuentes-Llanillo et al., 2021). Details of calculating carbon emissions are provided in

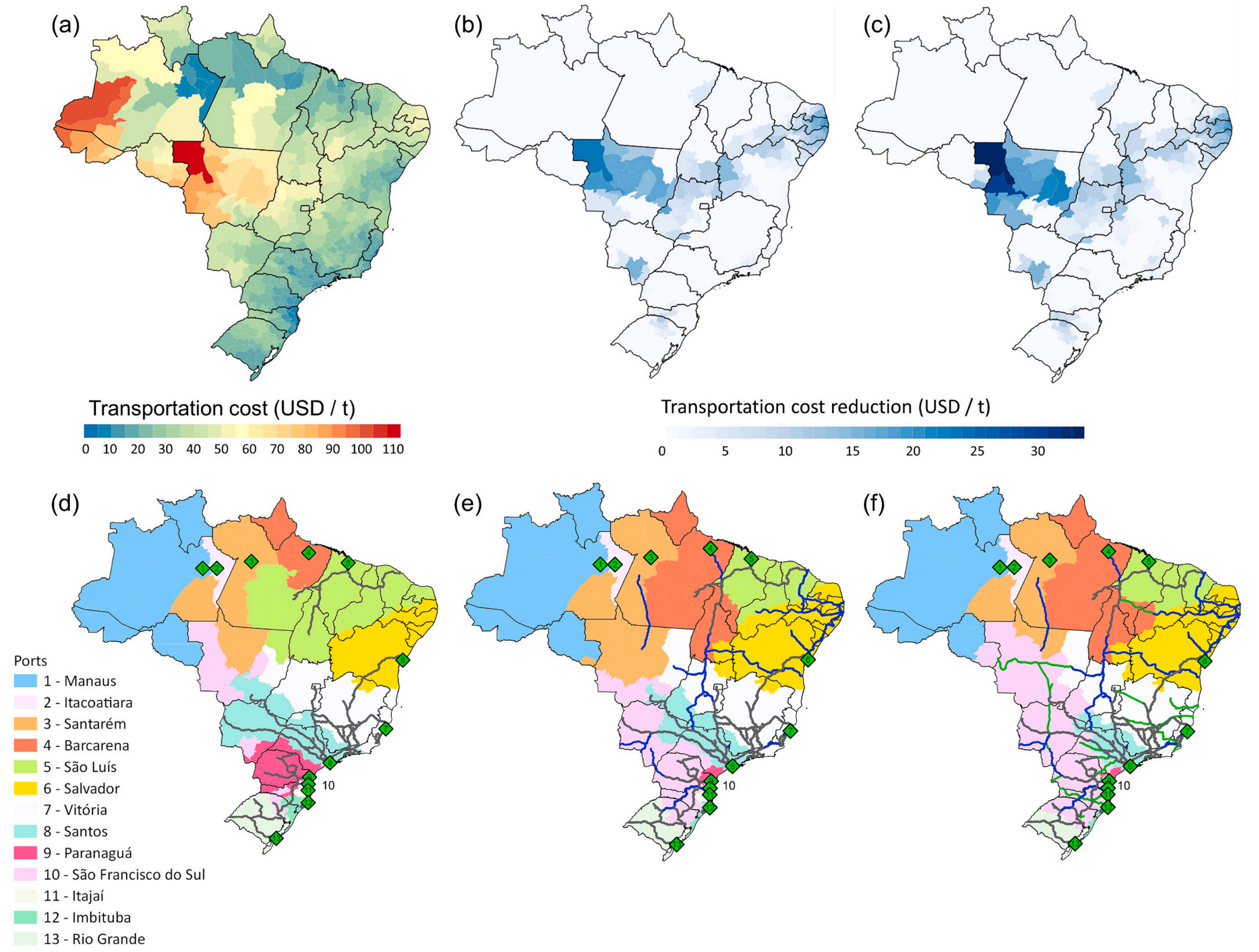


Fig. 4. Impact of transportation infrastructure on estimated transportation cost and port hinterland at micro-region level. Upper row: the transportation cost at the baseline of 2017 (a), the reduction between baseline and scenario Low (b), and the reduction between baseline and scenario High (c). Lower row: colors of micro-regions depict the port with the least transportation cost at baseline (d), scenario Low (e) and High (f). Railway network and port locations are adopted from Fig. 2.

supplementary material A.4.

3.4. Uncertainty

While model uncertainty is dependent on a host of factors, we focus on the following three due to their close connections to the land use outcomes that appear to be critical in the analysis. Foremost among these is the assumption about factor mobility, i.e., the potential for agricultural labor and capital to move across regions within Brazil as new regional economic opportunities open up. Empirical studies have found that the construction of transportation infrastructure would facilitate the labor movement both across geographic regions (Chein and Assunção, 2016) and also across agricultural and non-agricultural sectors (Huang et al., 2022), but estimates of the impact on labor movement with planned expansion of PNL2035 are not yet available. To evaluate the potential impact of PNL2035 on labor and capital movement across regions, we perform a bounding analysis. Specifically, we explore the implications of two extreme labor and capital mobility scenarios. At one extreme, we implement a "full mobility" scenario, in which factors (e.g., agricultural labor and capital) can move freely from one region to the other to obtain the highest return until a new equilibrium is reached. Given our simulation time horizon (2017–2035) of nearly two decades, the full mobility assumption seems quite plausible. At the other extreme, we consider the scenario by which labor and capital are wholly unresponsive to changing relative returns in other regions and are only supplied locally. This "no mobility" condition limits the capacity of agriculture to expand into regions with a growing comparative advantage following the PNL2035 scenarios. For purposes of bounding our findings, results are reported under both scenarios[9].

The second key driver of uncertainty in our results relates to the consequence of reduced cropland demand. For regions expecting changes in cropland demand, our default assumption is that land use conversion will occur between cropland and pasture, as the forest-pasture-cropland transition plays the dominant role in deforestation, while the forest-cropland transition takes a much smaller share (Nunes et al., 2022). Since we are not explicitly modeling the land use transition between pasture and forest, we explore a range of conversion possibilities in the areas with reduced cropland demand to show the sensitivity of carbon balance to the land use change driven by PNL2035.

The third key source of uncertainty in our results relates to land

---

[9] In order to capture the interactive effect of factor mobility and infrastructure expansion and to make simulations results under two factor mobility scenarios directly comparable, in the simulation of scenario BAU we used the basic full mobility scenario to create the baseline for 2035, then simulated low and high improvement scenarios with both no and full mobility scenarios.

supply elasticities, which govern the ease of movement of land in and out of crop production in response to changing cropland returns. These estimated land elasticity parameters are themselves uncertain and we sample from their estimated distributions in order to construct confidence intervals for the results. Details of sensitivity analysis are described in supplementary material A.6.

4. Results

4.1. Transportation cost and export competitiveness

For the current and planned infrastructure networks, we calculated the transportation cost in 2017, and its reduction under the scenario low and high from PNL2035 (Fig. 4, a–c)[10]. The baseline transportation cost from the production grids to coastal ports is higher in the inland Center-west region, especially Mato Grosso state, but much lower in the coastal regions. Transportation costs across Mato Grosso's regions range from $33/t to $112/t, and the state average is $68/t, or 28 % of the FOB price of exported crops. This stands in stark contrast with the average of $30/t or less for the Southeast-South Brazil. These estimates are quite comparable with the reported transportation cost in the closest period ($76.8/t from north Mato Grosso and $30.7/t in northwest Rio Grande do Sul) from USDA (Salin, 2023). With PNL2035, the largest transportation cost reductions arise in the Cerrado biome (Fig. 4 b and c). Under scenario Low, Bahia experiences the greatest reduction in transportation cost (23 %[11]), mainly due to the railway network across its western agricultural region (Fig. 2). Mato Grosso do Sul shows a similar magnitude in transportation cost reduction (22 %), followed by Mato Grosso (16 %) and Goiás (8 %). Under scenario High, the transportation cost reduction for Bahia (23 %), Mato Grosso do Sul (23 %), and Goiás (10 %) are little changed, indicating they mainly benefit from the infrastructure expansion already projected in scenario Low. On the other hand, the construction of new railways across Mato Grosso in scenario High further connect this state with the additional infrastructure network planned in scenario Low, which results in an even greater transportation reduction (22 %) compared with the baseline. In contrast with states in the Cerrado biome, PNL2035's effects on transportation cost reductions for Southeast-South states are relatively small, which are all <5 % for under scenario Low and <6 % under scenario High.

To gain an intuitive understanding for the cost reductions in Mato Grosso under scenario High, the reduction of $15/t (a 22 % reduction from the state average cost) is equivalent to the difference of transportation costs between from Mato Grosso to China (through North port) and from Iowa, USA to China (through the U.S. Gulf) reported for 2015 (Colussi and Schnitkey, 2022). The projected total transportation cost reduction by 2035 is estimated to be $1.39 billion, roughly equivalent to 1 % of Brazil's total value of agricultural production.

In addition to the impacts on crop transportation cost and export competitiveness for producers, the extension of the infrastructure network also influences the competitiveness between ports. Fig. 4 presents the relationship between each micro-region and the port connected with the least transportation cost under scenario BAU, Low and High. Panels 4d-f depict the change of port hinterland for crop commodities due to PNL2035. In northern Brazil, ports in São Luís (MA), which have been benefited from the existing railway network, will lose the relative advantage in transportation, as the North-South railway corridor and its extension toward Northeast and Center-West are constructed under PNL2035. Barcarena in the North and Salvador in the Northeast region show increased potential as ports for crop exports along Brazil's North coast. In South Brazil, the North-South railway corridor under scenario Low and the new corridor across Mato Grosso under scenario High will both contribute to the connectivity between major crop production regions in Cerrado with international market via ports on the South coast, in particular for São Francisco do Sul. Fig. 4 further shows that PNL2035 could also influence the competitiveness between the ports in North and South Brazil, as scenario Low favors the North and scenario High increases the relatively competitiveness of the ports in the South.

The shifts in preferential port destinations of crop production from the hinterland (Fig. 4d–f) also helps to explain the findings in transportation cost reduction. Take the northwest region of Mato Grosso as an example. On the baseline, farmers in this region take advantage of the railway network in South Brazil and would ship most of their harvests toward Southern ports. Under scenario Low, the new railway across the border between Mato Grosso and Pará (in Fig. 2) helps to reduce the transportation cost to northern ports, which changes this region's crop shipment to a much shorter and cheaper route to the north. Under scenario High, the new railway across the center of Mato Grosso further brings this region back to the hinterland of Southern ports with even lower transportation costs. In contrast, the adjacent region in the Amazonas and Pará already benefits from the proximity to Northern ports, and the expansion from railway network does significantly advantage Northern ports for this region, which results in only a slight reduction from PNL2035.

4.2. Land use and crop production

The revenue gains from the estimated transportation cost reduction increase farm profits, land rents, and eventually reshape the pattern of cropland use within Brazil (Fig. 5). For instance, under the scenario High with full mobility, cropland rents in Mato Grosso could rise by $233/ha, or a 96 % increase compared to the BAU scenario. In response to higher cropland returns, Mato Grosso alone is estimated to expand cropland area by a total of 847,226 ha as the region becomes better connected to domestic and global markets through the North–South–East–West railway corridors, which is equivalent to 10.7 % of the state's cropland area in 2017. In Southeast-South Brazil, although transportation cost modestly decreases, the demand for cropland in this region falls as it loses comparative advantage to the Cerrado. As a result, cropland area in Southeast-South Brazil is expected to shrink and regional cropland rents are projected to fall by 8–16 %. At the national level, cropland area changes only slightly, rising by 0.35 % under scenario High/No mobility and falling by −0.20 % under scenario High/Full mobility.

In addition to these cropland dynamics, the expansion of transportation infrastructure also changes yield and ultimately crop output by attracting agricultural labor and capital inputs into the Cerrado biome. Fig. 6 shows the percent change of crop output and its attribution to intensification, extensification, and their interactive effects at state level[12] (level values are provided in supplementary material A.5). Intensification of production, driven by increases in yield and multi-cropping (Martha Júnior and Lopes, 2023), explains the majority of the output change in the country. Crop output contracts by 6–10 % in the Southeast-South states (São Paulo, Minas Gerais, Paraná, and Rio

---

[10] In Fig. 4 (a), we observed the discontinuity in transportation cost in north Brazil. It is because in this study we estimated transportation cost at the micro-region level using the centroid of each micro-region as the origin. Furthermore, a micro-region in the Amazon biome is usually much larger than a micro-region in the northeast and south-southeast costal region, which causes the distance between two micro-region centroids and their disparity in transportation cost estimation to be greater, and the discontinuous pattern to be more obvious.

[11] The change of transportation cost at state level is calculated as the percentage change of average transportation cost (weighted by the crop production at gridded level in that state, to capture the spatial heterogeneity in crop production) between PNL2035 scenarios (low or high) and the baseline.

[12] In Fig. 6, we report results from the top eight crop producing states in Brazil. Aggregately, these states account for 81 % and 92 % of Brazil's cropland and crop output at 2017 baseline respectively, so they can represent the majority Brazilian agriculture. States are plotted with descending order of crop output in 2017.

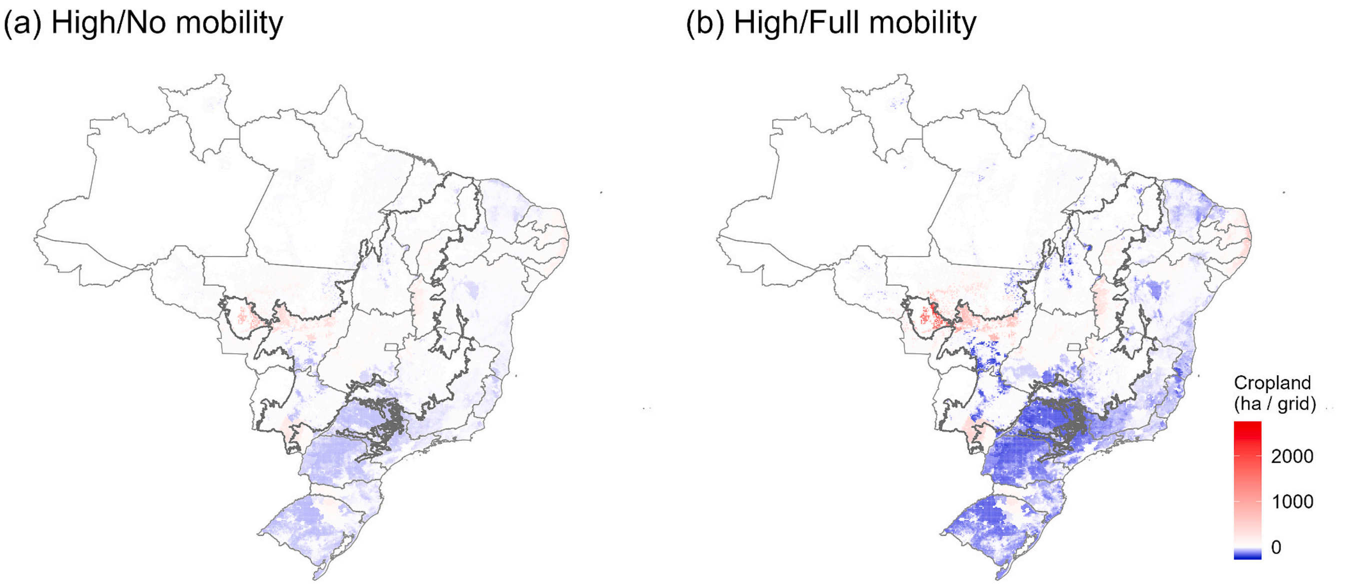


Fig. 5. Change of cropland area per grid under (a) High/No mobility and (b) High/Full mobility scenario, compared with scenario BAU. Gray line shows the boundary of states and the Cerrado biome.

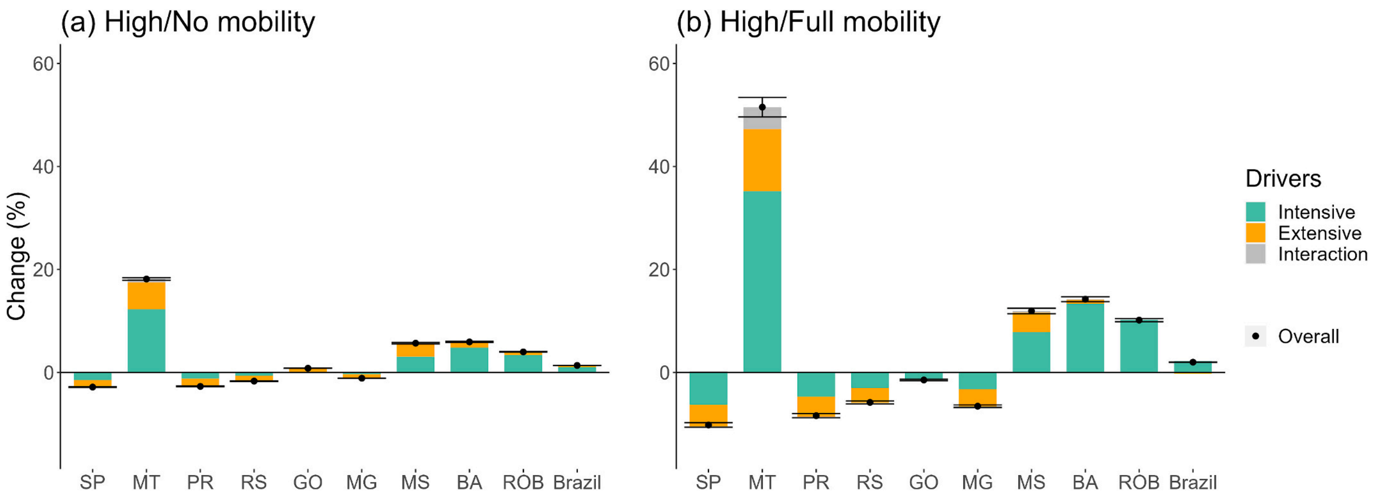


Fig. 6. Percentage change of crop output and the decomposition into changes in intensive (yield and multi-cropping) and extensive (cropland area) responses under (a) High/No mobility and (b) High/Full mobility scenarios, compared with scenario BAU. Results are shown by the top eight crop producing states, the aggregation of other 19 states as the rest of Brazil (ROB), and the national total (Brazil). Error bars show the 95 % confidence interval of crop output (In this paper, all 95 % confidence intervals are calculated based on the sensitivity analysis of uncertainty from cropland supply elasticity estimations (supplementary material A.6.1).).

Grande do Sul) due their loss of relative advantages but increases in the Cerrado, led by Mato Grosso and followed by Bahia and Mato Grosso do Sul.

The comparison between the two mobility scenarios is striking. Under the full mobility assumption, whereby agricultural labor and capital depart in favor of higher returns in the Cerrado regions (thought to be the most appropriate assumption for this multi-decade analysis), the changes (both increases and decreases) of both crop output and cropland use are more pronounced. While the no factor mobility assumption is likely unrealistic, it does provide a useful lower bound on the possible production changes. From Fig. 6 (a and b) we can see that the total increase in output in Mato Grosso is reduced by more than half under no factor mobility (51 % vs. 18 %). The production contraction in the Southeast (SP and MG) and South (PR and RS) regions is also greatly dampened. These findings highlight the important role of labor and capital mobility in determining the impact of transport infrastructure investments. This sensitivity to factor mobility carries over to the results on changes in carbon emissions from Brazil. Nonetheless, the aggregate impact on Brazil's national crop output is quite similar regardless of the factor mobility assumption: +1.4 % with no mobility vs. with +2.0 % with full mobility. As the increase in Brazil's crop output boosts crop export to the global market, we also find the crop output and cropland area in non-Brazil regions to decrease slightly (0.3 % or less) due to PNL2035 (please refer to supplementary material A.5.2 for results in non-Brazil regions).

4.3. *Carbon emissions from transport mode and land use*

Fig. 7 reports the impact of infrastructure expansion on carbon

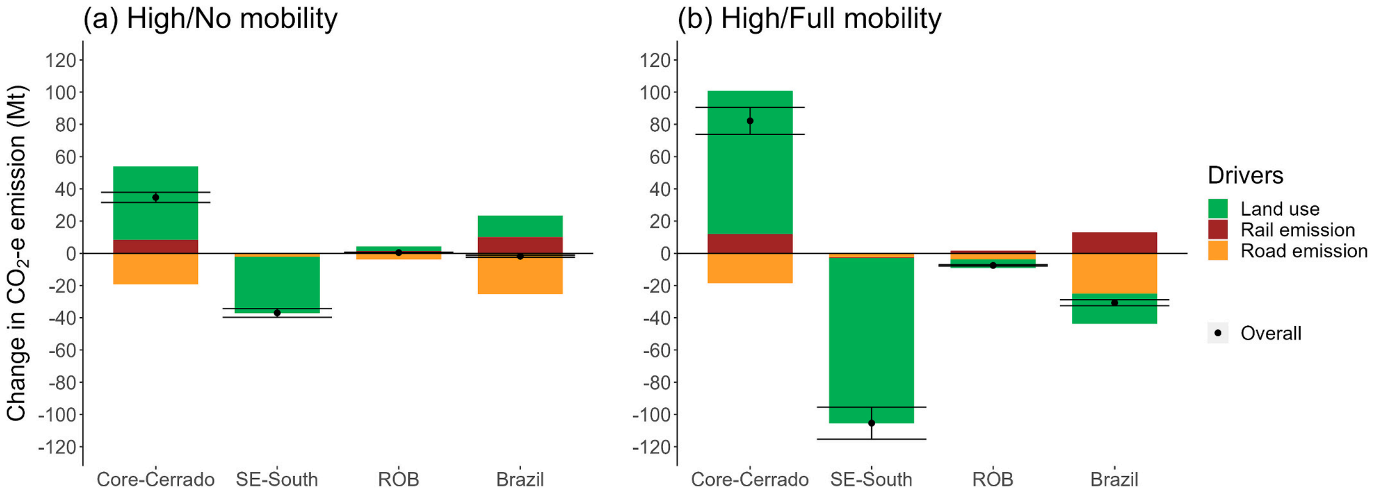


Fig. 7. Change of CO_2-equivalent emission on sub-national and national level and the decomposition by drivers under (a) High/No mobility and (b) High/Full mobility scenarios, compared with scenario BAU. Error bars show 95 % confidence interval.

emissions at the national and subnational[13] levels under scenario High and both mobility conditions. In addition, it is reported the decomposition into direct (road and railway emission separately) and indirect (from land use conversion) channels, measured in million metric tons of carbon dioxide equivalent ($MtCO_2$-e).

Railway expansion causes the shifting of cargo transportation mode from roadways to the more fuel-efficient railway transport, and results in net reductions of carbon emissions from vehicles for all sub-national regions and at the national level (Fig. 7). The largest carbon emission added by railway comes from the Core-Cerrado biome due to both longer railway length and larger freight volume caused by increased agricultural production. However, this is more than offset by the reduction in carbon emissions from the less-efficient road transportation. At the national level, the net carbon emissions reduction attributed solely to transport mode change is 11.9 $MtCO_2$-e under scenario High.

Infrastructure expansion can indirectly impact carbon emissions through land use conversion, although the final effect is dependent on labor and capital mobility for reasons shown above. When assuming land use conversion happens between cropland and pasture, under the scenario High with full factor mobility, carbon emissions in Core-Cerrado biome are expected to increase by 88.9 $MtCO_2$-e due to carbon stock loss from cropland expansion over pastureland (Fig. 7b). Conversely, in the Southeast-South region, carbon emissions would be reduced by 102.4 $MtCO_2$-e from the restoration of pasture on areas with reduced cropland demand, while the carbon emission reduction from land use is relatively small in the rest of Brazil (5.3 $MtCO_2$-e). Thus, at the national level, PNL2035 causes net carbon emissions to decrease by 18.8 $MtCO_2$-e from land use change, and the total carbon emission reduction (land use change and vehicle emission) reaches 30.7 $MtCO_2$-e, which is equivalent to 1.57 % of Brazil's total emissions in 2017 (SEEG, 2022). However, when labor and capital inputs are fixed locally, both the cropland expansion in the Core-Cerrado biome and the amount of high carbon stock land that can be freed up from farming in Southeast-South regions are reduced (Fig. 5 a). The response in carbon emissions from land use becomes much smaller for both the Cerrado (increased by 45.6 $MtCO_2$-e) and Southeast-South regions (decreased by 35.1 $MtCO_2$-e), and the rest of Brazil shows a slight increase in carbon emissions from land use (2.9 $MtCO_2$-e) (Fig. 6 a). Consequently, the no mobility condition overturns the carbon emission-saving from land use conversion (i.e., an increase of 13.5 $MtCO_2$-e),[14] and almost eliminates the total reductions of carbon emission (decrease by just 1.8 $MtCO_2$-e).

Finally, a key factor determining infrastructure expansion's impacts on carbon balance is the uncertainty about future land use decisions in areas with reduced demand for cropland. Fig. 8 shows the potentially vast difference in national net carbon emissions (y-axis), depending on the percentage of cropland exiting agriculture in Southeast-South Brazil that is actually converted to vegetation (x-axis)[15] and the type of vegetation (pasture, planted forest, and natural forest) into which the reduced cropland demand is converted. We find that to achieve carbon neutrality (zero change in total carbon emission), it requires the minimum of 86 % (0.96 million ha) of the reduced cropland demand to be converted to pasture. The minimum conversion share to achieve carbon emission neutrality falls to 50 % (0.56 million ha) and 32 % (0.36 million ha), respectively, if we assume the reduced cropland demand ends up as planted or natural forest.

5. Discussion

High transportation costs in Brazil, especially inland, have been a major barrier hampering the expansion of Brazil's agricultural output and exports (Gale et al., 2019; Meade et al., 2016; Tiller and Thill, 2017). Additionally, the presence of inordinately high transport costs distorts the allocation of resources across geographically dispersed production units within and across sectors of the economy (Adamopoulos, 2011). Despite the decades-long persistence of this problem in the Brazilian economy, its impacts have not been sufficiently researched, especially in the context of a multi-scale analysis capable of capturing local to regional and global responses relevant to the agricultural sector and to the environment.

In this study, we approached this knowledge gap by utilizing a fusion

---

[13] For the convenience of analysis at sub-national level, we group those top eight crop producing states to two sub-national regions: Core-Cerrado (the Center-West region and Bahia): Mato Grosso (MT), Goiás (GO), Mato Grosso do Sul (MS) and Bahia (BA); and Southeast-South (denoted as SE-South): São Paulo (SP), Paraná (PR), Rio Grande do Sul (RS) and Minas Gerais (MG). For states that locates both in Cerrado region and Southeast-South region (for example MG and SP), we group them based on the location of the major crop producing areas within the state.

[14] Due to rounding, the sum of sub-national values and national total is slightly different.

[15] Here we assume the rest of reduced cropland demand (not converted to national vegetation) has zero carbon stock. If the carbon stock for the rest of land is non-zero, it would further decrease carbon emission. So, Fig. 8 shows the upper bound of simulated carbon emission in view of uncertainties in land conversion.

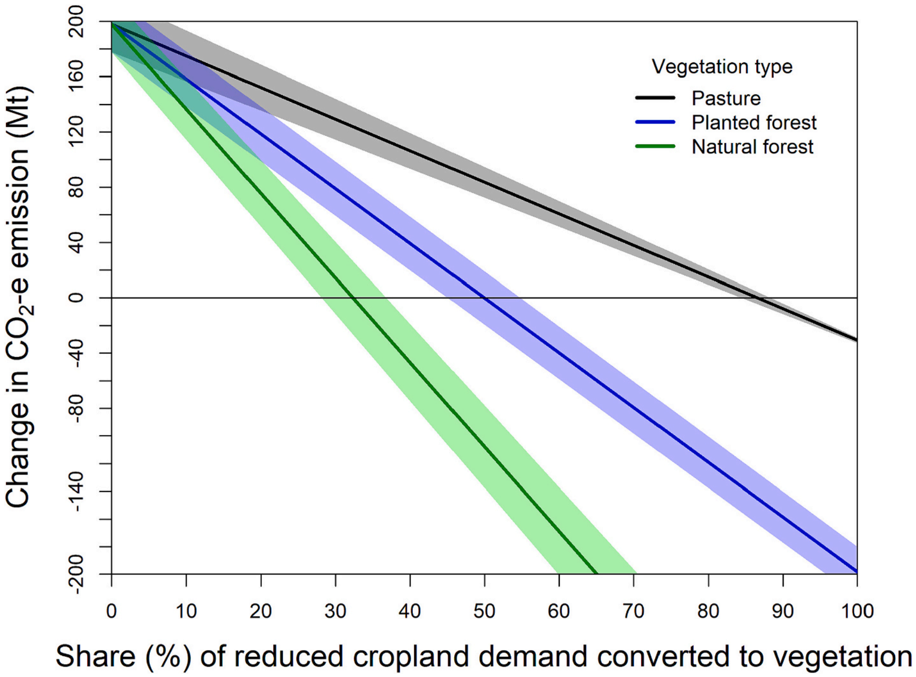


Fig. 8. Relationship between national carbon emission ($MtCO_2$-e) and the share (%) of abandoned cropland in Southeast-south Brazil that is converted to different vegetation types under the High/Full mobility scenario, with 95 % confidence interval (shade).

of geospatial datasets relating to the current and future transport infrastructure in Brazil, as indicated by the newly launched National Logistic Plan for 2035. In contrast to existing literature that aims to identify the optimal cost-minimizing configuration of logistics flows at subregional level (da Silva and de Almeida D'Agosto, 2013; de Oliveira et al., 2022, 2021) or provides grid-specific time-based indexes for transportation convenience but without overlying actual costs (Weiss et al., 2018; Victoria et al., 2021; Fontanilla-Diaz, 2021), our method of quantifying transportation cost bridges these two streams of literature and allows for the computation of actual freight cost at gridded level. This allows us to embed the freight cost into a spatially explicit economic model to simulate global and regional demand- and supply-equilibria, resulting in spatialized economic and environmental impacts of Brazil's planned logistic transformation.

With the increasing availability of geospatial data, this approach has the potential to be generalized to other regions worldwide for purposes of assessing the consequences of infrastructure investments for fine-scale economic and environmental outcomes. Furthermore, a promising direction for future studies is to develop a hybrid model (Tao et al., 2016) that uses both raster-based transportation friction and also vector data on existing transportation networks. The hybrid model approach would combine the advantage of the existing method for representing both on-road (rail) and off-road (rail) transportation, while also better accounting for transportation infrastructure features (volume, status, direction) and possible policy restrictions.

Using the grid-resolving multi-scale model SIMPLE-G-Brazil, we investigated the endogenous responses of Brazilian agriculture by 2035, taking both socio-economic development and infrastructure expansion into consideration. The evolution of Brazilian agricultural output over our baseline period (increase by 28.5 % from 2017 to 2035 in the BAU scenario) is largely driven by macro-economic developments in income, population and productivity at home and abroad. It is expected that reduced transportation costs would have the potential to boost agricultural output and exports. In the presence of the proposed infrastructure investments, Brazil's total agricultural output by 2035 would be around 2.0 % higher than the BAU scenario. Conversely, limited impacts on global agricultural outputs and cropland changes are identified (Supplemental material A.5).

On the other hand, the distribution of agricultural production within Brazil – and hence its associated environmental impacts – is heavily influenced by the projected developments in transportation infrastructure. Under scenario High, PNL2035 results in differential freight cost reductions between the states in the Cerrado biome (varies between 10 % to 23 %) and in Southeast-South regions of Brazil (< 6 %), which considerably improve the competitiveness of crop production and exporting from Cerrado. As a result, PNL2035 would link inland farmers more closely to urban and international markets. The effect of transportation cost reduction further reinforces the relative advantage of agricultural production in the Cerrado, diverting crop production away from the more traditional agricultural regions.

Our findings pose some important questions about the prospects for future land use changes in Cerrado biome and Brazil more generally. During the 1985–2021 period, about 28 million ha of the Cerrado were converted into some sort of agricultural use; soybean area increased the most (18.4 million ha), followed by land conversion to pastures (9.3 million ha), according to data from MapBiomas (collection 7). Although the deforestation rates in the Cerrado have decreased from the peak of 2.57 million ha/year on average, in 2001–2005, to 0.72 million ha/year, in 2016–2020, a recent spike in the deforestation rate (0.96 million ha/year during 2021–2022) raises concerns about future deforestation trends in the Cerrado biome again (TerraBrasilis, 2023).

The expansion of infrastructure has been identified as a major driver in land use conversion in the Cerrado biome (Prudêncio da Silva et al., 2010), but the absolute size of its impacts and potential spillovers are still under debate. Although studies reported effects of cropland expansion and deforestation following transportation network projects (Araujo et al., 2023; de Barros and Baggio, 2021; Donaldson and Hornbeck, 2016; Laurance et al., 2015; Reid and De Sousa, 2005; Thomas, 2006), some authors have argued that replacing road transportation with railways could slow down deforestation. They argue that the rail network could circumvent the “fishbone effects” (the construction of secondary roads by sides of the main road, which enhances the access to natural forest) (Viana et al., 2008), limit carbon emissions from transportation and deforestation (Prudêncio da Silva et al., 2010; Ribeiro et al., 2021; Holler Branco et al., 2022), and reduce the ecological environmental pressures (Jiang and Liu, 2022).

Our findings suggest that one key element for reconciling these opposing views is the spatial spillover effect, which is closely related to the "emissions leakage" discussed in the environment and climate literature (Aukland et al., 2003; Henders and Ostwald, 2012). Its implications for conservation have also been examined by Pfaff et al. (2007) and Dou et al. (2018). Our study further confirms the existence of important spatial spillover effects from transportation infrastructure expansion: railway expansion intensifies agricultural production and terrestrial carbon emissions in the Cerrado, but also shifts crop production away from Southeast-South regions due to the change in relative advantages in farming. Combined with the more emission - efficient transportation mode, the infrastructure expansion yields the potential for an overall land and carbon saving effect at the national level, but this effect depends on the mobility of labor and capital within Brazil as well as uncertainties in the responsiveness of cropland conversion. Overlooking the possible opposing responses to PNL2035 across regional scales would give rise to misleading evaluations of the impacts of the policy. Finally, as the carbon emission from transportation infrastructure expansion is mainly caused by cropland expansion in Cerrado, further studies are needed to understand the interactive effects between the extension of infrastructure and the strengthening of conservation polices.

Besides the potential impacts on both agricultural and environmental goals, PNL2035 could also pose challenges to regional and sectoral development as well as local environments when livestock production and pastureland conversion are also taken into consideration. A salient example is the cropland expansion and the potential environmental stresses evidenced in Mato Grosso. We have assumed that the additional cropland in this region will come from pastureland. This, in turn, creates additional pressure to either expand pasture or intensify livestock production systems. The recent trajectory of beef productivity in Brazilian pastures indicates that freeing up pasture to other uses, without compromising output, is quite achievable (Cohn et al., 2014; Martha et al., 2012, 2024). Indeed, pasture area peaked in Brazil in 2006 (160.42 million ha) and since then has been declining. According to the most recent data from Mapbiomas (collection 7), in 2021, the pasture area was 151.14 million ha. However, this does not rule out the possible response of increased conversion of forests to pasture, which takes the majority share in Brazilian deforestation (Nunes et al., 2022). Also, increasing stocking rates in pastoral systems, without appropriate grazing management and attention to soil fertility, may lead to pasture degradation (Leal Filho and Esteves de Freitas, 2018) and increased carbon emissions (Cardoso et al., 2016; Latawiec et al., 2014). Clearly, incorporating pastureland use response to livestock production and the corresponding forest-pasture transition into the SIMPLE-G-Brazil framework would be a valuable addition to our analysis of infrastructure's agricultural and environmental impacts.

Another challenge posed by PNL 2035 is its impact on the dynamics of Brazilian port throughput (Estadão Conteúdo, 2022; Notteboom and Rodrigue, 2005; Souza et al., 2023). Recently there has been a boom in private ventures (mainly by overseas investors) to develop port infrastructure along the "Northern Arc" to divert corn and soybean exports from the traditional Southeast-South ports to the Northern ports in Brazil (Colussi and Schnitkey, 2022; Estadão Conteúdo, 2022). In view of the on-going infrastructure construction (the scenario Low of PNL2035), our findings on port hinterland support the need for the investment in Northern ports. However, these findings also indicate that the long-run investment in ports should take the further extension of infrastructure (scenario High) and its impact on port competitiveness into consideration. Furthermore, to meet the growing demand for the 'last mile' trucking between rail and port terminals (Costa et al., 2021), investments in modern ports and the accompanying storage capacity will be necessary. Policies and regulations need to be put in place to ensure that this is done in an efficient manner. Our analysis could contribute to the efficient allocation of port infrastructure investment by revealing the effects of transportation infrastructure on national crop production, besides logistics pattern and associated port throughput projections. Finally, besides the expansion of the transportation network, the national pattern of transportation costs also depends on possible changes in export ports. While we assume all ports remain active and no additional ports are constructed by 2035, future studies exploring the interactions between port construction plans, the transportation infrastructure network and agricultural and environmental responses could provide important insights for policymakers and stakeholders.

As with any such modeling study, there are important limitations to this work that should be noted here and which could point the direction for future studies. First of all, we have assumed that all of the transport cost reductions are passed through to agricultural producers. However, it is possible that market power on the part of the railway firms, as well as seasonal congestion, might lessen the pass-through of these cost savings to farmers. In this case, our estimates of farmers' revenue gain from infrastructure expansion should be interpreted as an upper bound. Second, in this study we aggregated multiple crops to corn-equivalent using the price weight calculated with data from the 2017 baseline. Although this aggregation relieves the demand for crop-specific parameterization of the model, it assumes that disaggregated crop prices move in tandem over the long run to 2035 (more than a decade). This assumption could be relaxed in future research by updating the model with crop-specific production functions, data and parameters.

A third limitation relates to the incorporation of railway terminals and intermodality into the analysis, once the location of future terminals on the planned extensions become available. Incorporating terminal locations into the analysis will further improve the accuracy of route identification and cost estimation. Fourth, our estimation of transportation cost and distance is based on the shapefile of current and planned transportation network. We recognize that this dataset does not include other features of road networks such as road status and pavement. Thus we were forced to use the average speed of paved and unpaved road to represent road transportation. Further, secondary infrastructure such as rail spurs, which are not included on the shapefile cannot be taken into the current analysis. Lack of detailed information on the transportation system will circumscribe the accuracy of our cost estimation. This highlights the need for improved transportation data.

A fifth limitation relates to the use of unit cost rates ($R/t) in the study. However, when transporting commodities in large volumes, in particular with railways, the marginal cost will decrease with the quantity shipped, which further changes the unit cost rate. Further data on transportation cost rates and quantities could allow for this relationship to be estimated. Sixth, one major challenge we faced in this study is the uncertainty stemming from the transportation infrastructure's impact on labor mobility across regions and across sectors. Although the potential impact on labor mobility across regions can be bounded with two extreme scenarios (no mobility and full mobility), it is difficult to apply the same approach for mobility across sectors, since the non-agricultural sectors are not modeled at grid level due to data availability. As a result, we must leave the mobility across sectors outside of our current research scope. Future studies with better regional data on non-agricultural sectors could shed light on the interactions between infrastructure and labor mobility across both regions and sectors.

Last, but not least, transportation infrastructure expansion will not only improve the farm-gate price of crops, but also reduce the farm-gate price of purchased inputs, such as fertilizer, which are typically imported and must therefore utilize the same transportation network. Future studies estimating the impact of the transportation cost reduction on purchased inputs are also needed. Adding these cost reductions could potentially accentuate the shift in the geography of agricultural production in Brazil, and future studies should use specific-designed models to more accurately test the potential impacts in the global arena.

6. Conclusion

The transportation cost of agricultural commodities has been an obstacle to Brazil's agricultural production and export competitiveness. Using a novel approach to estimating freight cost by grid cells across Brazil and embedding this in a grid-resolving model of Brazilian agricultural production, we estimate that the national logistic plan PNL2035 has the potential to reduce transportation costs in the Cerrado biome by up to 23 %. This markedly narrows the gap in freight cost between farmers in the interior of Brazil and their competitors on global crop market. As a result, PNL2035 will dramatically alter the spatial distribution of crop production within the country. Agricultural output could increase by 51 % in Mato Grosso, relative to baseline, driven mostly by increases in yield and multi-cropping due to the relative advantage from reduced transportation cost.

In contrast to Mato Grosso, in the traditional producing states of São Paulo, Paraná and Rio Grande do Sul, agricultural output is projected to decrease by as much as 10 % due to the shifting of crop production patterns. This results in a significant shift in land use within Brazil with cropland expanding by as much as 1 million ha in the Cerrado while declining in the Southeast-South. Provided the reduced cropland demand reverts to pasture, the PNL 2035 has the potential to reduce Brazil's national carbon emissions by 30.7 $MtCO_2$-e, a combined effect attributed to both land use change (−18.8 Mt) and the transportation mode switch (−11.9 Mt). Reforesting this reduced cropland demand would generate much larger carbon reductions. However, the impacts of PNL2035 also depend on its effects on enhancing labor and capital mobility within the country. In the extreme case of no mobility, the response in crop production and land use is damped by more than half, and the reduction in carbon emission is almost eliminated.

This analysis of PNL 2035 clearly demonstrates the value of multiscale analysis for studies linking transport infrastructure investments and sustainability. This approach has the potential to be adopted more broadly as a framework to detect heterogeneous local responses to large-scale policies and convey market signals across spatially separated regions of the national economy. This enables more comprehensive and better-informed policy design and evaluation.

CRediT authorship contribution statement

Zhan Wang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Data curation, Conceptualization. **Geraldo B. Martha:** Writing – review & editing, Supervision, Resources, Funding acquisition, Data curation, Conceptualization. **Jing Liu:** Writing – review & editing, Supervision, Software, Project administration, Methodology, Conceptualization. **Cicero Z. Lima:** Writing – review & editing, Resources, Data curation, Conceptualization. **Thomas W. Hertel:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thomas W. Hertel reports financial support was provided by National Science Foundation. Geraldo B. Martha reports financial support was provided by Inter-American Development Bank. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank GLASSNET seminar participants for their helpful comments and discussion on the manuscript.

Funding sources

This work was supported by the National Science Foundation projects: “CNH2-L: Uncovering Metacoupled Socio-Environmental Systems” [DEB-1924111, 2019] and “GLASSNET” [OISE-2020635, 2021], as well as the Inter-American Development Bank project “Projeto Rural Sustentável – Cerrado” (IDB Technical Cooperation #BR-T1409) and Fapesp's Project “Integração cana-de-açúcar/pecuária: modelagem e otimização” (Fapesp, 2017/11523-5).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172434.

References

Adamopoulos, T., 2011. Transportation costs, agricultural productivity, and cross-country income differences. Int. Econ. Rev. 52, 489–521. https://doi.org/10.1111/j.1468-2354.2011.00636.x.

Aggarwal, S., 2018. Do rural roads create pathways out of poverty? Evidence from India. J. Dev. Econ. 133, 375–395. https://doi.org/10.1016/j.jdeveco.2018.01.004.

Aguiar, A., Chepeliev, M., Corong, E.L., McDougall, R., van der Mensbrugghe, D., 2019. The GTAP data base: version 10. Journal of Global Economic Analysis 4, 1–27. https://doi.org/10.21642/JGEA.040101AF.

Amann, E., Baer, W., Trebat, T., Lora, J.V., 2016. Infrastructure and its role in Brazil's development process. Q. Rev. Econ. Finance 62, 66–73. https://doi.org/10.1016/j.qref.2016.07.007.

Amann, E., Baer, W., Trebat, T., Lora, J.V., 2018. Infrastructure. In: Amann, E., Azzoni, C. R., Baer, W. (Eds.), The Oxford Handbook of the Brazilian Economy. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780190499983.013.20.

Araujo, R., Assunção, J., Bragança, A.A., 2023. The Effects of Transportation Infrastructure on Deforestation in the Amazon: A General Equilibrium Approach (Policy Research Working Papers).

Asher, S., Novosad, P., 2020. Rural roads and local economic development. American Economic Review 110, 797–823. https://doi.org/10.1257/aer.20180268.

Asher, S., Garg, T., Novosad, P., 2020. The ecological impact of transportation infrastructure. Econ. J. 130, 1173–1199. https://doi.org/10.1093/ej/ueaa013.

Assunção, J., Bragança, A., Araujo, R., 2020. The Environmental Impacts of the Ferrogrão Railroad: An Ex-Ante Evaluation of Deforestation Risks. In: Climate Policy Initiative.

Aukland, L., Costa, P.M., Brown, S., 2003. A conceptual framework and its application for addressing leakage: the case of avoided deforestation. Clim. Pol. 3, 123–136. https://doi.org/10.3763/cpol.2003.0316.

Baldos, U.L.C., Hertel, T.W., 2012. SIMPLE: A Simplified International Model of agricultural Prices, Land use and the Environment (GTAP Working paper 39).

Baldos, U.L.C., Haqiqi, I., Hertel, T.W., Horridge, M., Liu, J., 2020. SIMPLE-G: a multiscale framework for integration of economic and biophysical determinants of sustainability. Environ. Model. Software 133, 104805. https://doi.org/10.1016/j.envsoft.2020.104805.

Barber, C.P., Cochrane, M.A., Souza, C.M., Laurance, W.F., 2014. Roads, deforestation, and the mitigating effect of protected areas in the Amazon. Biol. Conserv. 177, 203–209. https://doi.org/10.1016/j.biocon.2014.07.004.

Bicudo Da Silva, R.F., Batistella, M., Moran, E., Celidonio, O.L.D.M., Millington, J.D.A., 2020. The soybean trap: challenges and risks for Brazilian producers. Front. Sustain. Food Syst. 4, 12. https://doi.org/10.3389/fsufs.2020.00012.

Bottasso, A., Conti, M., De Sa, Costacurta, Porto, P., Ferrari, C., Tei, A., 2021. Roads to growth: the Brazilian way. Res. Transp. Econ. 90, 101086 https://doi.org/10.1016/j.retrec.2021.101086.

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B.J.R., de Carvalho, I., das, N.O., de Barros Soares, L.H., Urquiaga, S., Boddey, R.M., 2016. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. Agr. Syst. 143, 86–96. https://doi.org/10.1016/j.agsy.2015.12.007.

Cattaneo, A., 2008. Regional comparative advantage, location of agriculture, and deforestation in Brazil. J. Sustain. For. 27, 25–42. https://doi.org/10.1080/10549810802225200.

Chein, F., Assunção, J.J., 2016. How does emigration affect labor markets? Evidence from road construction in Brazil. Brazilian Review of Econometrics 36, 157–184. https://doi.org/10.12660/bre.v99n992016.47740.

Cohn, A.S., Mosnier, A., Havlík, P., Valin, H., Herrero, M., Schmid, E., O'Hare, M., Obersteiner, M., 2014. Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. Proc. Natl. Acad. Sci. U. S. A. 111, 7236–7241. https://doi.org/10.1073/pnas.1307163111.

Colussi, J., Schnitkey, G., 2022. Investments in Brazilian Grain Transportation Shrink U.S. Logistical Advantage, 12. Farmdoc daily, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, p. 5.

CONAB, 2022. Portal de Informações Agropecuárias ("Agricultural Information Portal") [WWW Document]. Armazenagem e Logística ("Storage and Logistics"). URL. https://portaldeinformacoes.conab.gov.br/frete.html (accessed 4.12.22).

Costa, W., Davis, J., de Oliveira, A.R., Fernandes, F., Rajão, R., Soares Filho, B.S., 2021. Ferrogrão Railroad with a Freight Terminal in Matupá Will Split in half the Indigenous Lands of Xingu. Federal University of Minas Gerais - Policy Brief.

Costa, W., Soares-Filho, B., Nobrega, R., 2022. Can the Brazilian National Logistics plan induce port competitiveness by reshaping the port service areas? Sustainability 14, 14567. https://doi.org/10.3390/su142114567.

da Silva, M.A.V., de Almeida D'Agosto, M., 2013. A model to estimate the origin–destination matrix for soybean exportation in Brazil. J. Transp. Geogr. 26, 97–107. https://doi.org/10.1016/j.jtrangeo.2012.08.011.

Danielson, J.J., Gesch, D.B., 2011. Global multi-resolution terrain elevation data 2010 (GMTED2010). In: U.S. Geological Survey Open-File Report 2011–1073. US Department of the Interior, US Geological Survey, Washington, DC, USA.

das Neves, P.B.T., Blanco, C.J.C., Montenegro Duarte, A.A.A., das Neves, F.B.S., das Neves, I.B.S., de Paula dos Santos, M.H., 2021. Amazon rainforest deforestation influenced by clandestine and regular roadway network. Land Use Policy 108, 105510. https://doi.org/10.1016/j.landusepol.2021.105510.

de Barros, P.H.B., Baggio, I.S., 2021. The Spatial Relationship of Transportation Infrastructure and Deforestation in Brazil: A Machine Learning Approach (Presented at the Encontro Nacional de Economia, Online).

de Oliveira, A.L.R., Filassi, M., Lopes, B.F.R., Marsola, K.B., 2021. Logistical transportation routes optimization for Brazilian soybean: an application of the origin-destination matrix. Cienc. Rural 51, e20190786. https://doi.org/10.1590/0103-8478cr20190786.

de Oliveira, A.L.R., Marsola, K.B., Milanez, A.P., Fatoretto, S.L.R., 2022. Performance evaluation of agricultural commodity logistics from a sustainability perspective. Case Studies on Transport Policy 10, 674–685.

Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the Shared Socioeconomic Pathways. Glob. Environ. Chang. 42, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004.

Donaldson, D., 2018. Railroads of the Raj: estimating the impact of transportation infrastructure. Am. Econ. Rev. 108, 899–934. https://doi.org/10.1257/aer.20101199.

Donaldson, D., Hornbeck, R., 2016. Railroads and American economic growth: a "market access" approach*. Q. J. Econ. 131, 799–858. https://doi.org/10.1093/qje/qjw002.

Dou, Y., da Silva, R.F.B., Yang, H., Liu, J., 2018. Spillover effect offsets the conservation effort in the Amazon. J. Geogr. Sci. 28, 1715–1732. https://doi.org/10.1007/s11442-018-1539-0.

Economist Intelligence Unit, 2019. The critical role of infrastructure for the sustainable development goals. In: Economist Impact.

Escobar, N., Tizado, E.J., Zu Ermgassen, E.K.H.J., Löfgren, P., Börner, J., Godar, J., 2020. Spatially-explicit footprints of agricultural commodities: mapping carbon emissions embodied in Brazil's soy exports. Glob. Environ. Chang. 62, 102067 https://doi.org/10.1016/j.gloenvcha.2020.102067.

Estadão Conteúdo, 2022. Arco Norte ultrapassa outros portos em movimentação de soja e milho [WWW Document]. Canal Rural. URL. https://www.canalrural.com.br/noticias/agricultura/arco-norte-ultrapassa-outros-portos-em-movimentacao-de-soja-e-milho/ (accessed 2.7.23).

FAO, 2021. FAOSTAT: Food and Agriculture Data.

Fearnside, P.M., 2008. The roles and movements of actors in the deforestation of Brazilian Amazonia. E&S 13, art23. https://doi.org/10.5751/ES-02451-130123.

Ferraz, C., 2001. Explaining agriculture expansion and deforestation: evidence from the Brazilian Amazon - 1980/98. SSRN J. https://doi.org/10.2139/ssrn.294307.

Fliehr, Zimmer, Smith, 2019. Impacts of transportation and logistics on Brazilian soybean prices and exports. Transp. J. 58, 65. https://doi.org/10.5325/transportationj.58.1.0065.

FlowMap Group, 2022. The Least Cost Path Plugin for QGIS.

Fontanilla-Diaz, C.A., 2021. Roads, Deforestation, and GHG Emissions: The Role of Forest Governance and Carbon Tax Policy in Para and Mato Grosso, Brazil (PhD dissertation). Purdue University, West Lafayette.

Friedl, M., Sulla-Menashe, D., 2019. MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data Set] [WWW Document]. NASA EOSDIS Land Processes DAAC. https://doi.org/10.5067/MODIS/MCD12Q1.006 (accessed 10.11.22). URL.

Frohn, R., Dale, V., Jimenez, B., 1990. Colonization, Road Development and Deforestation in the Brazilian Amazon Basin of Rondonia (No. ORNL/TM-11470, 6946370, ON: DE90007968). https://doi.org/10.2172/6946370.

Fuentes-Llanillo, R., Telles, T.S., Soares Junior, D., de Melo, T.R., Friedrich, T., Kassam, A., 2021. Expansion of no-tillage practice in conservation agriculture in Brazil. Soil Tillage Res. 208, 104877 https://doi.org/10.1016/j.still.2020.104877.

Fuglie, K., 2022. International Agricultural Productivity [WWW Document]. Economic Research Service, USDA. URL. https://www.ers.usda.gov/data-products/international-agricultural-productivity/.

Gale, F., Valdes, C., Ash, M., 2019. Interdependence of China, United States, and Brazil in Soybean Trade. USDA.

Griffith, R., Redding, S., Reenen, J.V., 2004. Mapping the two faces of R&D: productivity growth in a panel of OECD industries. Rev. Econ. Stat. 86, 883–895.

Haqiqi, I., Bowling, L., Jame, S., Baldos, U., Liu, J., Hertel, T., 2023a. Global drivers of local water stresses and global responses to local water policies in the United States. Environ. Res. Lett. 18, 065007 https://doi.org/10.1088/1748-9326/acd269.

Haqiqi, I., Grogan, D.S., Bahalou Horeh, M., Liu, J., Baldos, U.L.C., Lammers, R., Hertel, T.W., 2023b. Local, regional, and global adaptations to a compound pandemic-weather stress event. Environ. Res. Lett. 18, 035005 https://doi.org/10.1088/1748-9326/acbbe3.

Havlík, P., Schneider, U.A., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., Cara, S.D., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., Obersteiner, M., 2011. Global land-use implications of first and second generation biofuel targets. Energy Policy 39, 5690–5702. https://doi.org/10.1016/j.enpol.2010.03.030.

Hayami, Y., Ruttan, V.W., 1985. Agricultural Development: An International Perspective, 2nd Edition. ed. The Johns Hopkins Press, Baltimore, Md/London.

Henders, S., Ostwald, M., 2012. Forest carbon leakage quantification methods and their suitability for assessing leakage in REDD. Forests 3, 33–58. https://doi.org/10.3390/f3010033.

Hertel, T.W., Baldos, U.L.C., 2016. Attaining food and environmental security in an era of globalization. Glob. Environ. Chang. 41, 195–205. https://doi.org/10.1016/j.gloenvcha.2016.10.006.

Holler Branco, J.E., Bartholomeu, D.B., Alves Junior, P.N., Caixeta Filho, J.V., 2022. Evaluation of the economic and environmental impacts from the addition of new railways to the Brazilian's transportation network: an application of a network equilibrium model. Transp. Policy 124, 61–69. https://doi.org/10.1016/j.tranpol.2020.03.011.

Horridge, J., Jerie, M., Mustakinov, D., Schiffmann, F., 2018. GEMPACK manual (GEMPACK software).

Huang, Q., Zheng, X., Wang, R., 2022. The impact of the accessibility of transportation infrastructure on the non-farm employment choices of rural laborers: empirical analysis based on China's micro data. Land 11, 896. https://doi.org/10.3390/land11060896.

IBGE, n.d. Population Density Map 2010.

Instituto Brasileiro de Geografia e Estatística (IBGE), 2019. Censo Agropecuário 2017 [WWW Document]. URL. https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2017/resultados-definitivos.

Jiang, C., Liu, X., 2022. Does high-speed rail operation reduce ecological environment pressure?—empirical evidence from China. Sustainability 14, 3152. https://doi.org/10.3390/su14063152.

Kasraian, D., Maat, K., Stead, D., Van Wee, B., 2016. Long-term impacts of transport infrastructure networks on land-use change: an international review of empirical studies. Transp. Rev. 36, 772–792. https://doi.org/10.1080/01441647.2016.1168887.

KC, S., Lutz, W., 2017. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. Glob. Environ. Chang. 42, 181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004.

Latawiec, A.E., Strassburg, B.B.N., Valentim, J.F., Ramos, F., Alves-Pinto, H.N., 2014. Intensification of cattle ranching production systems: socioeconomic and environmental synergies and risks in Brazil. Animal 8, 1255–1263. https://doi.org/10.1017/S1751731114001566.

Laurance, W.F., Goosem, M., Laurance, S.G.W., 2009. Impacts of roads and linear clearings on tropical forests. Trends Ecol. Evol. 24, 659–669. https://doi.org/10.1016/j.tree.2009.06.009.

Laurance, W.F., Peletier-Jellema, A., Geenen, B., Koster, H., Verweij, P., Van Dijck, P., Lovejoy, T.E., Schleicher, J., Van Kuijk, M., 2015. Reducing the global environmental impacts of rapid infrastructure expansion. Curr. Biol. 25, R259–R262. https://doi.org/10.1016/j.cub.2015.02.050.

Leal Filho, W., Esteves de Freitas, L. (Eds.), 2018. Climate Change Adaptation in Latin America: Managing Vulnerability, Fostering Resilience, Climate Change Management. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-56946-8.

Lima, C.Z., Martha, G.B., Barioni, L.G., Baldos, U.L.C., Hertel, T.W., 2022. Agricultural R&D Investments in Brazil: Global Responses and Local Spillovers (Presented at the 25th GTAP Annual Conference on Global Economic Analysis, Online).

Liu, J., Hertel, T.W., Lammers, R.B., Prusevich, A., Baldos, U.L.C., Grogan, D.S., Frolking, S., 2017. Achieving sustainable irrigation water withdrawals: global impacts on food security and land use. Environ. Res. Lett. 12, 104009.

Lopes, E., 2021. Entre porteiras e portos: A evolução da produção e exportação da soja e do milho no Brasil ("between Gates and Ports: The Evolution of Production and Export of Soybeans and Corn in Brazil"). CNA, Comissão Nacional de Logística e Infraestrutura.

Lucich, I.M., Villena, M.G., Quinteros, M.J., 2015. Transportation costs, agricultural expansion and tropical deforestation: theory and evidence from Peru. Cienc. Inv. Agr. 42, 153–169. https://doi.org/10.4067/S0718-16202015000200003.

Ludena, C.E., Hertel, T.W., Preckel, P.V., Foster, K., Nin, A., 2007. Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts. Agric. Econ. 37, 1–17. https://doi.org/10.1111/j.1574-0862.2007.00218.x.

MapBiomas, 2020. Project MapBiomas—Collection v4.1 of Brazilian Land Cover & Use Map Series.

Marin, F.R., Zanon, A.J., Monzon, J.P., Andrade, J.F., Silva, E.H.F.M., Richter, G.L., Antolin, L.A.S., Ribeiro, B.S.M.R., Ribas, G.G., Battisti, R., Heinemann, A.B., Grassini, P., 2022. Protecting the Amazon forest and reducing global warming via agricultural intensification. Nat Sustain 5, 1018–1026. https://doi.org/10.1038/s41893-022-00968-8.

Martha, G.B., Alves, E., 2018. Brazil's agricultural modernization and embrapa. In: Amann, E., Azzoni, C.R., Baer, W. (Eds.), Brazil's Agricultural Modernization and Embrapa. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780190499983.013.15.

Martha Júnior, G.B., Lopes, M.A., 2023. Charting new sustainable agricultural innovation pathways in Brazil. Sci. Agric. (Piracicaba, Braz.) 80, e20230067. https://doi.org/10.1590/1678-992x-2023-0067.

Martha, G.B., Alves, E., Contini, E., 2012. Land-saving approaches and beef production growth in Brazil. Agr. Syst. 110, 173–177. https://doi.org/10.1016/j.agsy.2012.03.001.

Martha, G.B., Barioni, L.G., Santos, P.M., Maule, R.F., Moran, D., 2024. Getting pastoral systems productivity right. Sci. Total Environ. 916, 170268 https://doi.org/10.1016/j.scitotenv.2024.170268.

Meade, B., Puricelli, E., McBride, W., Valdes, C., Hoffman, L., Foreman, L., Dohlman, E., 2016. Corn and soybean production costs and export competitiveness in Argentina, Brazil, and the United States. USDA Economic Information Bulletin 154, 53.

Metzger, J.P., Bustamante, M.M.C., Ferreira, J., Fernandes, G.W., Librán-Embid, F., Pillar, V.D., Prist, P.R., Rodrigues, R.R., Vieira, I.C.G., Overbeck, G.E., 2019. Why Brazil needs its legal reserves. Perspectives in Ecology and Conservation 17, 91–103. https://doi.org/10.1016/j.pecon.2019.07.002.

Meyfroidt, P., Börner, J., Garrett, R., Gardner, T., Godar, J., Kis-Katos, K., Soares-Filho, B. S., Wunder, S., 2020. Focus on leakage and spillovers: informing land-use governance in a tele-coupled world. Environ. Res. Lett. 15, 090202 https://doi.org/10.1088/1748-9326/ab7397.

Ministry of Infrastructure, 2022. NLP 2035: Brazil's National Logistics Plan to 2035.

Notteboom, T.E., Rodrigue, J.-P., 2005. Port regionalization: towards a new phase in port development. Marit. Policy Manag. 32, 297–313. https://doi.org/10.1080/03088830500139885.

Novaes, R.M.L., Pazianotto, R.A.A., Brandão, M., Alves, B.J.R., May, A., Folegatti-Matsuura, M.I.S., 2017. Estimating 20-year land-use change and derived CO $_2$ emissions associated with crops, pasture and forestry in Brazil and each of its 27 states. Glob Change Biol 23, 3716–3728. https://doi.org/10.1111/gcb.13708.

Nunes, C.A., Berenguer, E., França, F., Ferreira, J., Lees, A.C., Louzada, J., Sayer, E.J., Solar, R., Smith, C.C., Aragão, L.E.O.C., Braga, D.D.L., De Camargo, P.B., Cerri, C.E. P., De Oliveira, R.C., Durigan, M., Moura, N., Oliveira, V.H.F., Ribas, C., Vaz-de-Mello, F., Vieira, I., Zanetti, R., Barlow, J., 2022. Linking land-use and land-cover transitions to their ecological impact in the Amazon. Proc. Natl. Acad. Sci. U. S. A. 119, e2202310119 https://doi.org/10.1073/pnas.2202310119.

OECD, Food and Agriculture Organization of the United Nations, 2020. OECD-FAO Agricultural Outlook 2020–2029, OECD-FAO Agricultural Outlook. OECD. https://doi.org/10.1787/1112c23b-en.

ONTL, 2022. Simulador de Custo de Transporte ("Transport Cost Simulator") [WWW Document]. URL. https://ontl.epl.gov.br/aplicacoes/simulador-de-custo-de-transporte/ (accessed 3.15.22).

Pedlowski, M.A., Dale, V.H., Matricardi, E.A., da Silva Filho, E.P., 1997. Patterns and impacts of deforestation in Rondônia, Brazil. Landsc. Urban Plan. 38, 149–157.

Pfaff, A.S.P., 1999. What drives deforestation in the Brazilian Amazon? J. Environ. Econ. Manag. 37, 26–43. https://doi.org/10.1006/jeem.1998.1056.

Pfaff, A., Robalino, J., Walker, R., Aldrich, S., Caldas, M., Reis, E., Perz, S., Bohrer, C., Arima, E., Laurance, W., Kirby, K., 2007. Road investments, spatial spillovers, and deforestation in the Brazilian Amazon. J Regional Sci 47, 109–123. https://doi.org/10.1111/j.1467-9787.2007.00502.x.

Pires, M., 2022. Investimentos Públicos: 1947–2021 ("Public Investments: 1947–2021"). FGV, Observatório de Política Fiscal.

Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA2000—global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. Global Biogeochem. Cycles 24, 2008GB003435. https://doi.org/10.1029/2008GB003435.

Prado Siqueira, R., 2022. sidrar: An Interface to IBGE's SIDRA API.

Prudêncio da Silva, V.P., van der Werf, H.M.G., Spies, A., Soares, S.R., 2010. Variability in environmental impacts of Brazilian soybean according to crop production and transport scenarios. J. Environ. Manage. 91, 1831–1839. https://doi.org/10.1016/j.jenvman.2010.04.001.

Ray, S., Haqiqi, I., Hill, A.E., Taylor, J.E., Hertel, T.W., 2023. Labor markets: a critical link between global-local shocks and their impact on agriculture. Environ. Res. Lett. 18, 035007 https://doi.org/10.1088/1748-9326/acb1c9.

Reid, J., De Sousa, W.C., 2005. Infrastructure and conservation policy in Brazil. Conserv. Biol. 19, 740–746. https://doi.org/10.1111/j.1523-1739.2005.00699.x.

Ribeiro, F.N.D., Umezaki, A.S., Chiquetto, J.B., Santos, I., Machado, P.G., Miranda, R.M., Almeida, P.S., Simões, A.F., Mouette, D., Leichsenring, A.R., Ueno, H.M., 2021. Impact of different transportation planning scenarios on air pollutants, greenhouse gases and heat emission abatement. Sci. Total Environ. 781, 146708 https://doi.org/10.1016/j.scitotenv.2021.146708.

Rodrigues-Filho, S., Bursztyn, M., Lindoso, D., Debortoli, N., Nesheim, I., Verburg, R., 2012. Road development and deforestation in Amazonia, Brazil. In: Land Use Policies for Sustainable Development. Edward Elgar Publishing.

Rossi, C., Alfinito, A.C., 2023. Brazilian Supreme Court Judge Permits Analysis of Controversial Soybean Railway That Threatens the Amazon Rainforest and Severely Impacts Indigenous Land [WWW Document]. Amazon Watch. URL. https://amazonwatch.org/news/2023/0606-brazilian-supreme-court-judge-permits-analysis-of-controversial-soybean-railway-that-threatens-the-amazon-rainforest-and-severely-impacts-indigenous-land (accessed 6.23.23).

Salin, D., 2023. Soybean Transportation Guide: Brazil 2022. United States Department of Agriculture, Agricultural Marketing Service.

Santos, D.C., Souza-Filho, P.W.M., Da Rocha Nascimento, W., Cardoso, G.F., Dos Santos, J.F., 2020. Land cover change, landscape degradation, and restoration along a railway line in the Amazon biome, Brazil. Land Degrad. Dev. 31, 2033–2046. https://doi.org/10.1002/ldr.3514.

Schielein, J., Ponzoni Frey, G., Miranda, J., Souza, R.A. de, Boerner, J., Henderson, J., 2021. The role of accessibility for land use and land cover change in the Brazilian Amazon. Appl. Geogr. 132, 102419 https://doi.org/10.1016/j.apgeog.2021.102419.

SEEG, 2022. Total emissions [WWW Document]. The Greenhouse Gas Emission and Removal Estimating System (Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa). URL. http://seeg.eco.br (accessed 11.21.22).

Silva, J.G.D., Ruviaro, C.F., Ferreira Filho, J.B.D.S., 2017. Livestock intensification as a climate policy: lessons from the Brazilian case. Land Use Policy 62, 232–245. https://doi.org/10.1016/j.landusepol.2016.12.025.

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., Figueroa Meza, M.J., Fulton, L., Kobayashi, S., Lah, O., McKinnon, A., Newman, P., Ouyang, M., Schauer, J.J., Sperling, D., Tiwari, G., 2014. Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Souza, C.M., Z. Shimbo, J., Rosa, M.R., Parente, L.L., A. Alencar, A., Rudorff, B.F.T., Hasenack, H., Matsumoto, M., G. Ferreira, L., Souza-Filho, P.W.M., De Oliveira, S.W., Rocha, W.F., Fonseca, A.V., Marques, C.B., Diniz, C.G., Costa, D., Monteiro, D., Rosa, E.R., Vélez-Martin, E., Weber, E.J., Lenti, F.E.B., Paternost, F.F., Pareyn, F.G. C., Siqueira, J.V., Viera, J.L., Neto, L.C.F., Saraiva, M.M., Sales, M.H., Salgado, M.P. G., Vasconcelos, R., Galano, S., Mesquita, V.V., Azevedo, T., 2020. Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and earth engine. Remote Sens. (Basel) 12, 2735. https://doi.org/10.3390/rs12172735.

Souza, M.F. de, Tisler, T.R., Castro, G.S.A., Oliveira, A.L.R. de, 2023. Port regionalization for agricultural commodities: mapping exporting port hinterlands. Journal of Transport Geography 106, 103506. https://doi.org/10.1016/j.jtrangeo.2022.103506.

Tao, R., Strandow, D., Findley, M., Thill, J., Walsh, J., 2016. A hybrid approach to modeling territorial control in violent armed conflicts. Trans. GIS 20, 413–425. https://doi.org/10.1111/tgis.12228.

TerraBrasilis, 2023. Incrementos de desmatamento - Cerrado - Estados [WWW Document]. URL. http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/cerrado/increments (accessed 6.23.23).

the Ministry of Environment and Climate Change, n.d. Parna do Jamanxim [WWW Document]. Instituto Chico Mendes de Conservação da Biodiversidade. URL https://www.gov.br/icmbio/pt-br/assuntos/biodiversidade/unidade-de-conservacao/unidades-de-biomas/amazonia/lista-de-ucs/parna-do-jamanxim.

Thomas, V., 2006. From Inside Brazil: Development in the Land of Contrasts. Stanford University Press, The World Bank, Palo Alto, CA/Washington, DC. https://doi.org/10.1596/978-0-8213-6455-0.

Tiller, K.C., Thill, J.-C., 2017. Spatial patterns of landside trade impedance in containerized South American exports. Journal of Transport Geography 58, 272–285. https://doi.org/10.1016/j.jtrangeo.2017.01.001.

Valdes, C., 2022. Brazil's Momentum as a Global Agricultural Supplier Faces Headwinds. Amber Waves.

Vera-Diaz, M. del C., Kaufmann, R.K., Nepstad, D.C., Schlesinger, P., 2008. An interdisciplinary model of soybean yield in the Amazon Basin: the climatic, edaphic, and economic determinants. Ecol. Econ. 65, 420–431. https://doi.org/10.1016/j.ecolecon.2007.07.015.

Viana, V., Cenamo, M., Pavan, M., Carrero, G., Quinlan, M., 2008. Railroads in the Amazon: a key strategy for reducing deforestation. Carbon & Climate Law Review 2, 8. https://doi.org/10.21552/CCLR/2008/3/51.

Victoria, D. de C., Silva, R.F.B. da, Millington, J.D.A., Katerinchuk, V., Batistella, M., 2021. Transport cost to port though Brazilian federal roads network: dataset for years 2000, 2005, 2010 and 2017. Data Brief 36, 107070. https://doi.org/10.1016/j.dib.2021.107070.

Weinhold, D., Reis, E., 2008. Transportation costs and the spatial distribution of land use in the Brazilian Amazon. Glob. Environ. Chang. 18, 54–68. https://doi.org/10.1016/j.gloenvcha.2007.06.004.

Weiss, D.J., Nelson, A., Gibson, H.S., Temperley, W., Peedell, S., Lieber, A., Hancher, M., Poyart, E., Belchior, S., Fullman, N., Mappin, B., Dalrymple, U., Rozier, J., Lucas, T. C.D., Howes, R.E., Tusting, L.S., Kang, S.Y., Cameron, E., Bisanzio, D., Battle, K.E., Bhatt, S., Gething, P.W., 2018. A global map of travel time to cities to assess inequalities in accessibility in 2015. Nature 553, 333–336. https://doi.org/10.1038/nature25181.

World Bank, 2020. World Bank Open Data.

Yang, W., Wang, W., Ouyang, S., 2019. The influencing factors and spatial spillover effects of CO2 emissions from transportation in China. Sci. Total Environ. 696, 133900 https://doi.org/10.1016/j.scitotenv.2019.133900.

Zhao, X., Taheripour, F., Malina, R., Staples, M.D., Tyner, W.E., 2021. Estimating induced land use change emissions for sustainable aviation biofuel pathways. Sci. Total Environ. 779, 146238 https://doi.org/10.1016/j.scitotenv.2021.146238.

Zilli, M., Scarabello, M., Soterroni, A.C., Valin, H., Mosnier, A., Leclère, D., Havlík, P., Kraxner, F., Lopes, M.A., Ramos, F.M., 2020. The impact of climate change on Brazil's agriculture. Sci. Total Environ. 740, 139384 https://doi.org/10.1016/j.scitotenv.2020.139384.