Transportation Cost, Agricultural Production and Cropland Expansion in Brazil: A Multi-scale Analysis

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1. Introduction

Over the past decades, transportation cost has played an increasingly important role in Brazil agriculture. As demand for crops increases both domestically and internationally, agricultural production frontier in Brazil has been expanding much more rapidly in inland area in central west and the remote area in the north, where transportation system is less developed. The longer distance to the ports and the poor infrastructure can significantly increase the cost share of transportation. Taking soybean productions in Mato Grosso as an example, about 11% - 28% of its free-on-board price can be attributed to logistic and transportation cost (Fliehr, Zimmer, and Smith 2019).

High transportation cost has been found associated with less agricultural production and lower profitability. It reduces the revenue received by farmers in remoted area and increases the cost of inputs such as fertilizer, labor and machinery, resulting in lower than optimal yield (Vera-Diaz et al. 2008). Also, transportation cost increases the total cost of crop production, which would undermine the competitiveness of Brazil crop export to global market. These potential impacts give Brazil strong incentives to reduce domestic transportation cost in order to increase agricultural profitability. However, the more profitable agriculture could also trigger cropland expansion and deforestation (Lucich, Villena and Quinteros 2015), which may pose long-term threat to sustainability, as Jevons paradox indicates.

The impact of transportation cost and agriculture production and the environment has been researched from various scales and aspects. Using data from a collection of cities, Fliehr et al., (2019) report transportation cost explains the difference between producer price and free-on-board price, so reduction in transportation cost would increase producer price and return of land, contributing to the expansion of cropland. On aggregated level, Lucich et al., (2015) model transportation improvement as increase in labor efficiency due to reduced transportation time, and conclude it would trigger cropland expansion and deforestation on agricultural frontier. To capture the spatial heterogeneity of transportation, Schielein et al., (2021) measured the traveling time to storage and consumption sites on gridded level in Brazilian Amazon, and find better access to crop storage sites are associated with cropland cultivation significantly. Still, several gaps exist in existing literature. While studies focus more on the region where transportation cost is expected to change, the spillover effects for other regions through economic linkage are still not sufficiently researched. Also, existing studies tend to focus on single scale (aggregated or spatial), but not on multi-scale. To better understanding the impact of transportation change, it would be important to capture both spatial heterogeneity in transportation and agriculture and also macro-level drivers on population and economic growth, technology improvement and demand from international markets.

This study aims at examining the implications of transportation cost for Brazil agriculture with a multi-scale framework. Especially, we focus on the relationship between transportation cost reduction, agricultural production pattern and cropland expansion at the grid-cell level. Findings would contribute to the literature by providing evidence for heterogeneous local response to macro-level policies, as well as the spillover effect of transportation development.

2. Methodology

2.1 Estimation of transportation cost

The first step of analysis is to estimate transportation cost of crop for the whole Brazil on spatial level. In this study, we focus on the transportation cost of agricultural productions on road and railway, which are major transportation method in Brazil. According to Fliehr et al., (2019), road and railway transportation are responsible for 60% and 33% of soybean transportation respectively. Under the Ministry of Agriculture, Livestock and Food Supply, the National Supply Company (Conab) maintains a freight cost database[1], which contains 3,086 records of origin and destination, distance and transportation cost from survey or contract data for 925 routes. However, the database does not cover all sub-state regions in Brazil, leaving the transportation cost in those regions unknown. An alternative data source is the National Observatory of Transport and Logistics[2], which provides transportation cost (Real per ton) of agricultural production by rail or road as a function of distance (km), estimated from real-world data. Although this dataset can be used to calculate transportation cost for all sub-state regions, it is still necessary to have a reliable estimation of the distance from all possible origin of crop production to the destination. And existing studies evaluating each grids' access to destinations (cities or ports) have shown that the distance would be influenced by transportation network, land use and land scape (Weiss et al. 2018; Victoria et al. 2021), so using a straight distance would result in highly biased results.

In this paper, we combine existing literature on spatial accessibility estimation and the functional relation between distance, transportation method and cost and develop an integrated method to estimate transportation cost of crop on gridded level for Brazil. Take 2017, the baseline of our analysis, as an example (Figure 1). First, we collect the road (blue routes in (a)) and railway (red routes in (a)) network as shapefile from the National Logistic Plan of Brazil and rasterize it at 30 second resolution.

Second, we calculate a friction surface of transportation at the same resolution, which

[1] https://portaldeinformacoes.conab.gov.br/frete.html
[2] https://ontl.epl.gov.br/

represents the inconvenience of transporting on the grid cell as the inverse of speed (unit: minutes required to travel one meter). For grids that are not located on the road or railway network, we first take the land cover data from MODIS land use dataset (MCD12Q1.006) and assign a base traveling speed for each land cover type, then adjust the traveling speed based on the elevation and slope with on the Global Multi-resolution Terrain Elevation dataset of 2010 (GMTED2010). Base traveling speed and landscape adjustment function are based on Weiss et al., (2018). Then all speed data (km /h) are inversed and converted to friction (min / meter). For grids that are located on the road network, we assign a speed of 65 km / hour, which is the average of transportation speed on paved and unpaved road in Brazil (Schielein et al. 2021), and converted it to friction as well. For grids that are located on the railway network, although the transportation speed is reported to be within the range of 80 km / h to 40 km / h (and decrease to 12 km / h when approaching to cities) (Fliehr 2013), the marginal transportation cost is only half of that on road, according to National Observatory of Transport and Logistics' function. Thus here we take the same traveling speed as road transportation for railway, but assign an adjustment of 50% less on the friction to represent the preference of railway transportation due to lower marginal cost. With the friction surface (b), we can identify the route between any two grids with least accumulated friction. Since the friction of grids on railway and road would be much lower than grids that are not, the identified the route would represent the dependence on transportation network in (a). Furthermore, for each identified route, we can calculate the length that overlapped with the railway network, as the estimated distance travelled on railway.

Third, according to official administrative definition, the whole Brazil consists of 558 micro-regions (gray polygon in (c)), which is equivalent with county level and are able to capture sub-state level heterogeneity. For each micro-region[3], we identified the centroid of its polygon as the origin and represents all grids on the same polygon in distance calculation. Destinations of transportation are represented by 16 active exporting ports (yellow starts in (c)), based on Victoria et al., (2021). Here we select exporting ports as destinations of crop transportation because Brazil is a major exporter of crop on global markets. Also, those ports are close to more developed southern costal area, which are also major destinations of domestic consumption. For each origin-destination part, we use the friction surface and least accumulated friction algorithm to identify a route and calculate the distance on railway or not respectively. Then the two distance are further plugged into transportation cost function from the National Observatory of Transport and Logistics to calculate railway and road transportation cost, as well as the estimated total cost as the sum. Then for each origin, the least total cost

[3] One micro-region is located on eastern island, which is outside of friction layer and is omitted from the analysis. So we use 557 micro-region in total for the analysis.

among routes to all destinations are selected to represent the estimated transportation cost of crop. Finally, we use the estimated transportation cost of each origin to represent the corresponding micro-region, which end up with the estimation of transportation cost for crop on gridded level for the whole Brazil. In this method, we use QGIS 3.16 to rasterize shapefile, calculate slope, match with railway, measure distance and identify polygon centroid. Also, the least accumulated friction algorithm is performed using "least cost path" plugin of QGIS. While the calculation of transportation and identification of least cost is conducted with R 3.6.2.

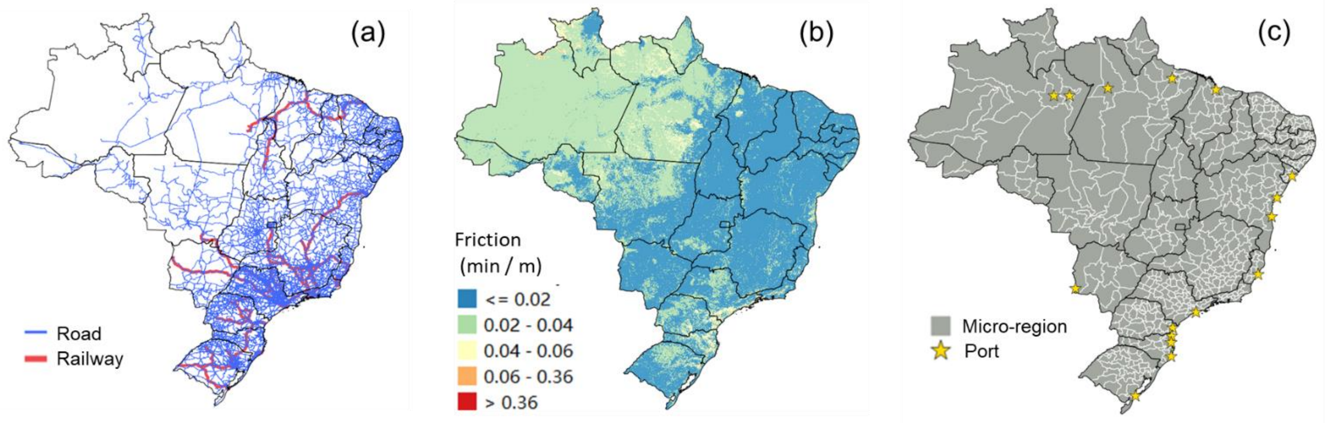

Figure 1. Procedure of estimating transportation cost

Applying this method, we calculate the gridded transportation cost for Brazil in 2017 as baseline. In order to validate this method, we further calculate the transportation cost data using the same set of origin and destination from Conab, and compare estimated cost with reported cost. Also, using the projection of road and railway network by 2035 according to the National Logistic Plan, maximum improvement scenario, we also calculate the future transportation cost, in order to simulate the impact of transportation cost change in Brazil.

2.2 Evaluation of transportation cost's impact on agriculture

With the transportation cost data estimated in section 3.1, the next step is to simulate its impact on agricultural production in Brazil. Here we develop a grid-resolving partial equilibrium model on Brazilian agriculture, the Simplified International Model of agricultural Prices, Land use and the Environment: Gridded version for Brazil (SIMPLE-G-Brazil). The SIMPLE-G-Brazil model downscales Brazil to 50,598 five arc-minute grid cells, while keeping the rest of world aggregated to 16 regions. Given changes in global and national drivers (e.g. population and GDP growth, technology development and biofuel expansion), the model simulates the spatial pattern of crop production and inputs use (cropland, fertilizer, labor, and water) at the grid-cell level. These local responses are further aggregated to the whole Brazil, in order to achieve equilibrium at the national and eventually global level. The base line year of the model is 2017.

To research the impact of transportation improvement on agriculture, we use SIMPLE-G-Brazil to simulate the difference between two transportation scenarios under five socio-economic develop scenarios. The two transportation scenarios are (1) maximum improvement of transportation network in National Logistic Planning and (2) counterfactual scenario: if the transportation network remains at the 2017 level, so their difference represents the upper bound of transportation cost's impact from policy side. The five socio-economic scenarios are the projection of population, GDP per capita, technology and demand of biofuel for both Brazil and other 16 regions representing major economies under five Shared Socioeconomic Pathways (SSPs). Here the SSP2: "Middle of the road:" is selected as the base reference of socio-economic projection, while the other four SSPs provides a range of possible variance under uncertainties of future development. The transportation scenarios are established using the method described in section 2.1, socio-economic scenarios are based on projections from OECD Env-Growth model and Wittgenstein Centre (WiC), IIASA. Simulation of SIMPLE-G-Brazil model is performed with GEMPACK 12.0.

3.Result

3.1 Validation of transportation cost estimation method

To test the accuracy of transportation cost estimation, here we use the method described in section 2.1 on origins and destinations from Conab transportation database to estimate transportation distance and cost of each route, and compare these estimation results with real-world data reported in the database. Here we use the road and rail network in 2017 for this validation, which is the closet transportation network available to the period of Conab data (since 2014). For comparison purpose, the original data of transportation cost in Conab database are all converted to Real in 2017, using CPI of Brazil from the World Bank.

First, we use the estimated and reported data to fit a linear model for distance (km) and transportation cost (Real / ton) respectively:

$$y = \alpha + \beta x$$

Where y refers to data reported in Conab database, x refers to data estimated using our methodology, β is the coefficient of estimated data, which indicates the linear relation between y and x and α is the constant term. As is shown in table 1, in both regressions we have the coefficient of estimated data to be significant at 0.01 level. And we cannot reject the hypothesis that these coefficients equal to 1 using t-test ($p \approx 1$). Furthermore, both model has R-squared over 0.8, indicating the majority of variance in reported distance and transportation cost can be explained by the same variable estimated with our method. While the regression also indicates the constant to be non-zero, these constants is generally small comparing with the data (median of reported distance and transportation cost are 1636 km and 221.21 Real / ton respectively). In general, regression results indicate close match of real-world data and that estimated with our estimation method.

Table 1. Regressions of reported and estimated distance and transportation cost

	Distance	Transportation cost
alpha	-36.470***	8.981***
	(13.703)	(2.406)
beta	1.035***	1.038***
	(0.007)	(0.010)
obs	2903	2903
R^2	0.894	0.804

Note: results reported in each cell is coefficient (standard error). Significance sign: *: 0.10; **: 0.05; ***: 0.01

Furthermore, we visualize the comparison of estimated and reported distance and transportation cost on figure 2. The 1:1 red line is also attached for the convenience of interpretation. For transportation distance, scatter points are located around the red line with variance increases with the distance, which indicates estimation errors may accumulate with distance. For transportation cost, we also find the scatter points locates around the red line, but some points show vertical pattern. The reason of this pattern is that Conab database may include multiple records of a single route, whose transportation cost varies with year or season. While in our method, the transportation cost is calculated with cost-distance function estimated with pooled data over time, so each unique route would only have one estimated cost but multiple reported cost, resulting in the vertical pattern shown in figure 2 (right).

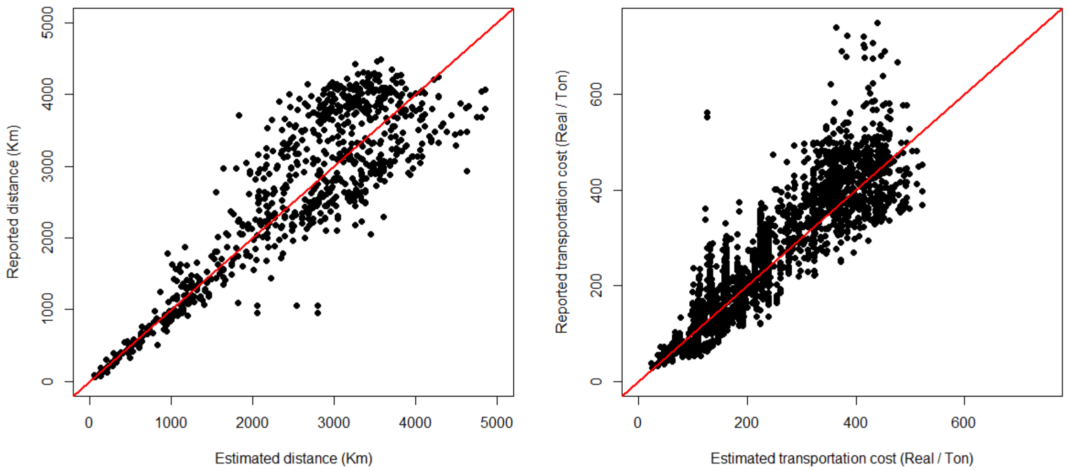

Figure 2. Comparison of estimated and reported distance (left) and transportation cost (right)

3.2 Transportation cost: baseline and projection

Based on validation of transportation cost estimation, we apply the method for all micro-region in Brazil to calculate the transportation cost of crop to exporting ports. Here transportation cost is converted to US dollars per ton using the official exchange rate from the World Bank, in order to match with the other monetary data in SIMPLE-G-Brazil in next step of analysis.

Figure 3 shows the estimation of transportation cost for whole Brazil at the baseline of 2017, measured both in monetary term and also as share in farm-gate price faced by farmers[4]. Region with highest transportation cost is western Amazon and Acre, with transportation cost up to 90~100 USD / ton (equivalent to 60~70% of farm-gate price). Regions with second-highest transportation cost is northwestern Mato Grosso, where transportation cost is around 80~90 USD / ton (50~60 % of farm-gate price).Reasons of high transportation cost in these regions are that transportation network is much sparser in western Brazil than eastern (figure 1 (a)), and these regions are far from ports (figure 1 (c)). However, they may not have the same impact on agriculture. For the region in Amazon and Acre state, land cover is dominated by forest so the high transportation cost' impact on crop production is limited. While the Mato Grosso state is the inland agricultural frontier in Brazil and major producer of soybean, so the high transportation cost of regions within Mato Grosso would have severer negative impact on local agricultural production, which would be further analyzed with model simulation. For regions closer with ports and have more dense transportation network, for example along eastern coast, have much lower transportation cost and higher farm-gate price.

[4] In this study, farm-gate price is calculated as the global crop price (assuming same crop price at all exporting ports – global competition), minus the transportation cost from origin (each micro-region) to destination (exporting ports). Then the share is calculated as transportation cost divided by farm-gate price.

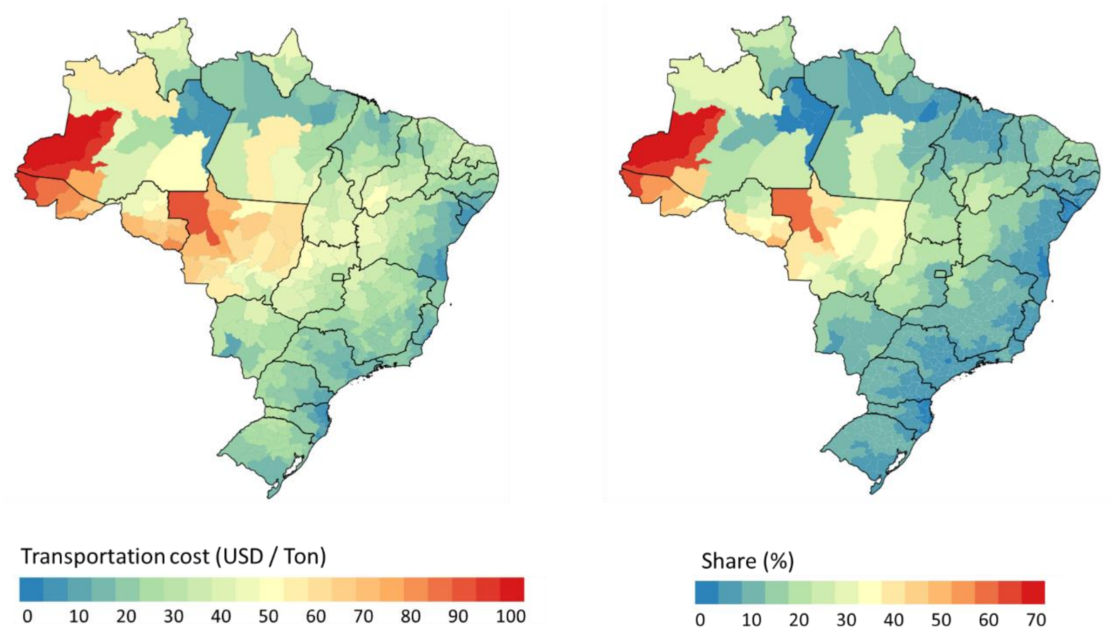

Figure 3. Estimated transportation cost in baseline (left) and as share in farm-gate price (right)

To project how transportation cost would change in Brazil, we refer to the National Logistic Planning of Brazil, which provides scenarios of transportation improvement by 2035. Here the maximum improvement scenario is selected to provide the upper bound of projected transportation cost reduction. Using the same estimation method, the transportation cost under maximum improvement scenario and the reduction from baseline level as percentage change is shown in figure 4. The majority of improvement is expected to happen in central Mato Grosso, western Bahia, northern Mato Grosso do Sul and western Santa Catarina, with transportation cost to reduce by 30~40% at the baseline level. The major reason of transportation reduction is plans to build new railway, which reduces both the distance to ports, and also the transportation cost per kilometer. The estimated change in transportation cost (figure 4 (right)) is then used as the exogenous shock in SIMPLE-G-Brazil to calculate its impact of agricultural input and output use, together with other shocks for future projection.

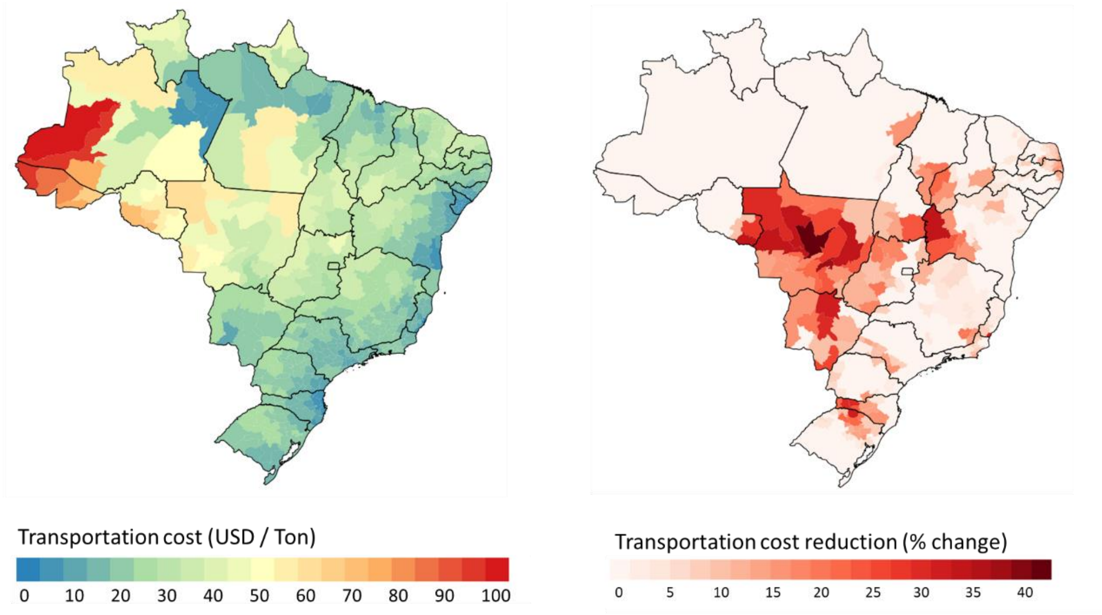

Figure 4. Estimated transportation cost in Max improvement scenario (left) and transportation cost reduction from baseline in percentage change (right)

3.3 Impact of transportation cost on agriculture

Using SIMPLE-G-Brazil, we simulate the difference of two transportation scenarios under five socio-economic development scenarios, to provide a possible range of impact of transportation cost reduction under different development projects. Results of percentage change in crop output, cropland input and labor-capital input use are shown in figures 5 – 7 respectively. For better interpretation, impacts on states that ranks top 10 in crop outputs at baseline are presented separately. These states together represent 85% of cropland and 95% of output for whole Brazil at the baseline, so they can represent the majority of impact in Brazil. On the other hand, impacts on the resulting 17 states are aggregated together and shown as "rest of Brazil" on these figures as well. Taking SSP2 as the reference level, the reduction of transportation cost results in crop output to increase by 80.5% in Mato Grosso, followed by 23.6% increase in Bahia and slight increase in Santa Catarina and rest of Brazil, both below 2%. For other states, the reduction of transportation cost results in decrease of crop output, but at relatively smaller magnitude (10% and less). When transportation cost decreases, the farm-gate price faces by farmer would increase, which improves the profitability of farming and encourages crop production to be concentrated in these states and decrease in other states, indicating the spillover effect of transportation cost change in the whole economic system. The magnitude of transportation cost change is higher in SSP4 "Inequality" and lower in SSP3 "Rivalry", with other SSPs within the range, and the impact of diffident SSPs is to amplify the impact on the baseline level.

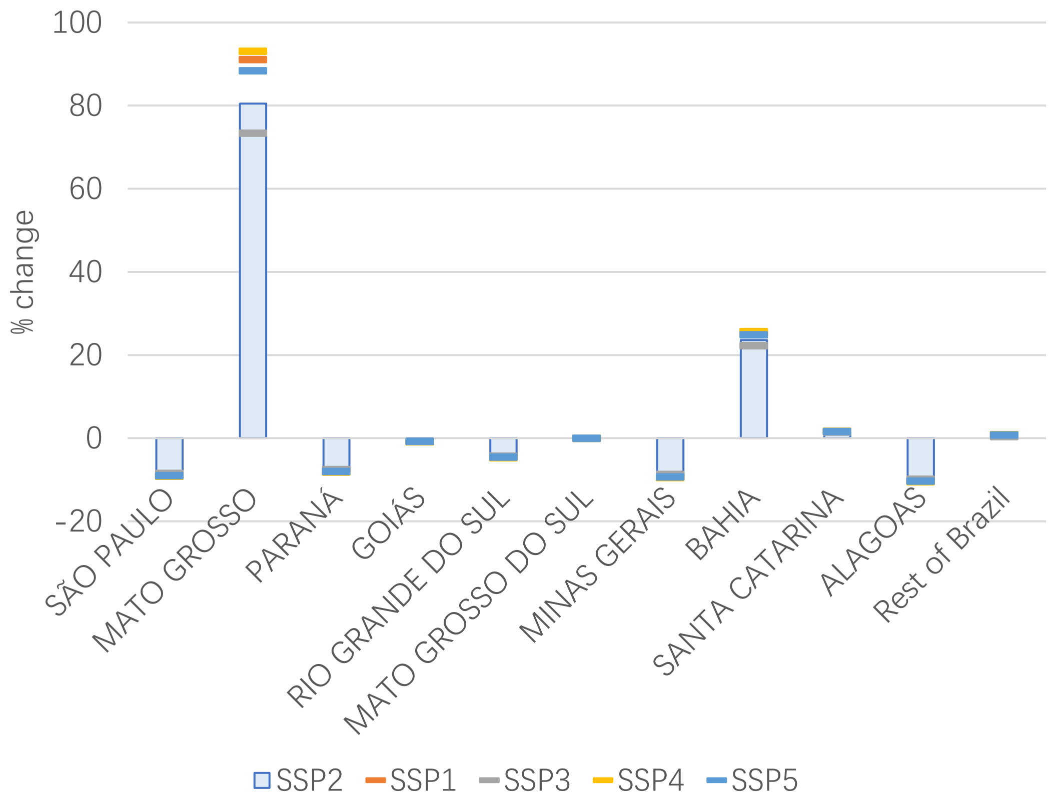

Figure 5. Impact of transportation improvement on crop production

The increase of crop output results from increase of use in both cropland and non-land inputs, as is shown in figure 6 and 7. The state-level patterns of impact on these inputs are similar with output in figure 5, but at different magnitude: with transportation cost reduction, cropland use changes by smaller percentage than output, while labor-capital change is higher. Comparing with cropland supplied locally, the labor-capital input is modelled to have national mobility, which makes it easier to intensify labor-capital input use to for higher yield and output in regions experiences transportation cost reduction.

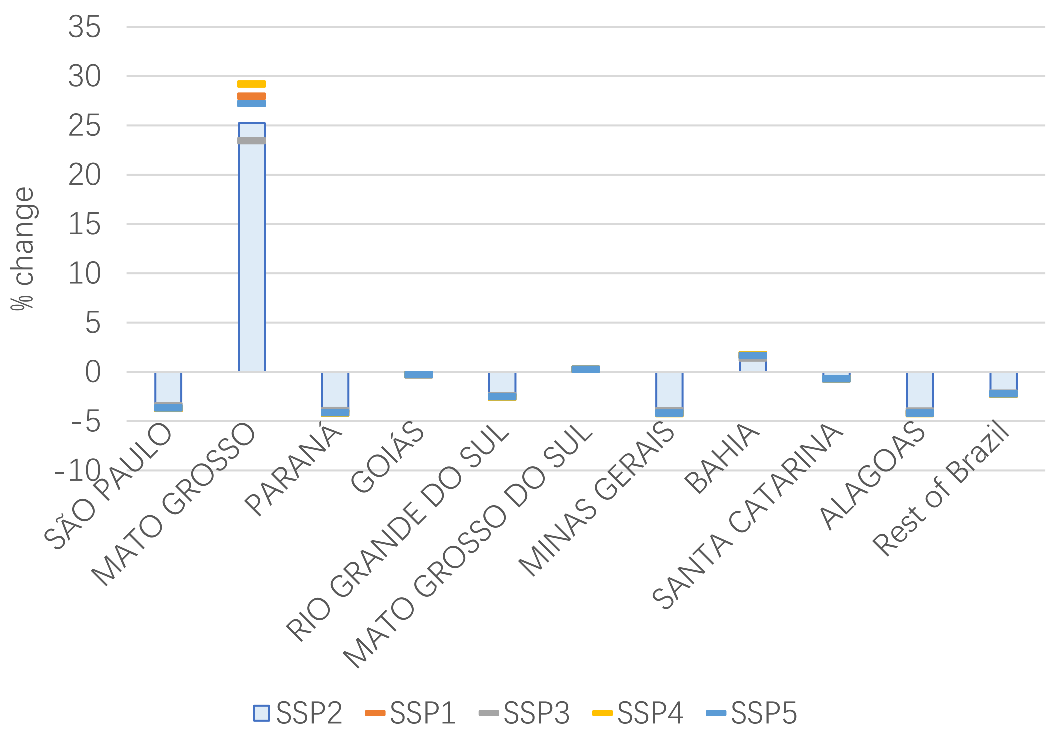

Figure 6. Impact of transportation improvement on cropland use

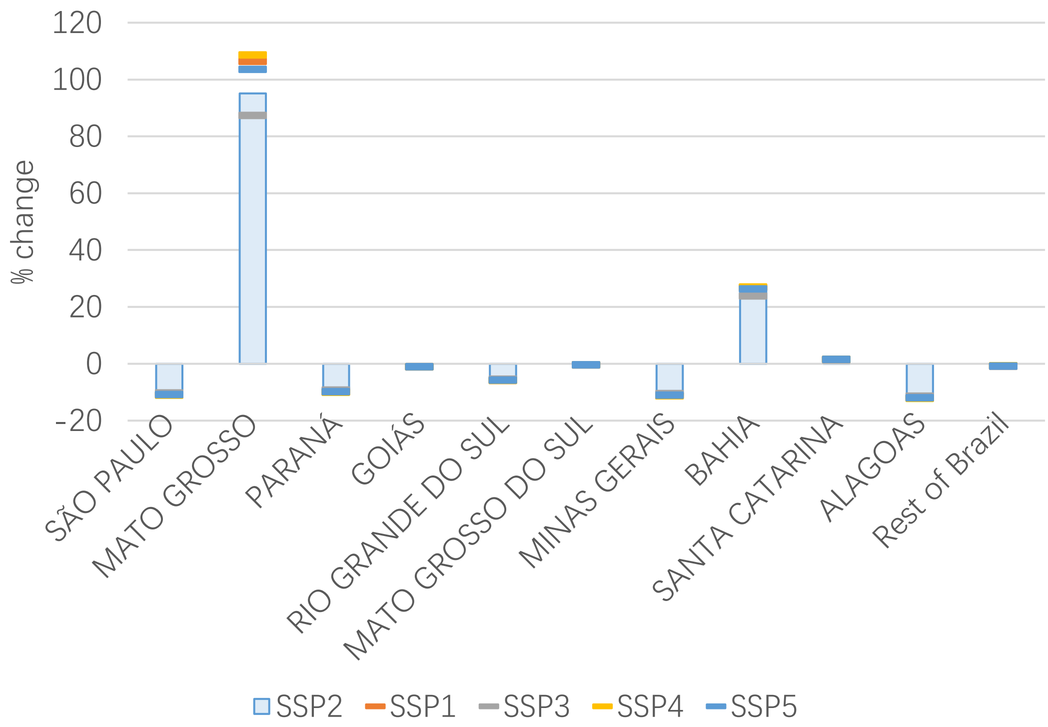

Figure 7. Impact of transportation improvement on labor-capital input use

Response of crop output would also change the impact of transportation improvement to total transportation cost for all outputs in each state. As is shown in figure 8, when the change in total transportation cost is decomposed by change in cost per ton and change in total crop output in ton, we find that although most of major crop-producing states and rest of Brazil would have lower transportation cost due to infrastructure improvement in National Logistic Planning, in Mato Grosso and Bahia thus impact would be offset by increase in crop output, even driving the total transposition cost to increase in Mato Grosso. While in states like Sao Paulo, Parana, Rio Grande do Sul and Minas Gerais, total transportation cost would decrease by higher degree, due to the reduction of crop output in these states. Decomposition results shown here indicates the importance to evaluate overall effect of policy under the economic framework that captures rebounding and spillover effect.

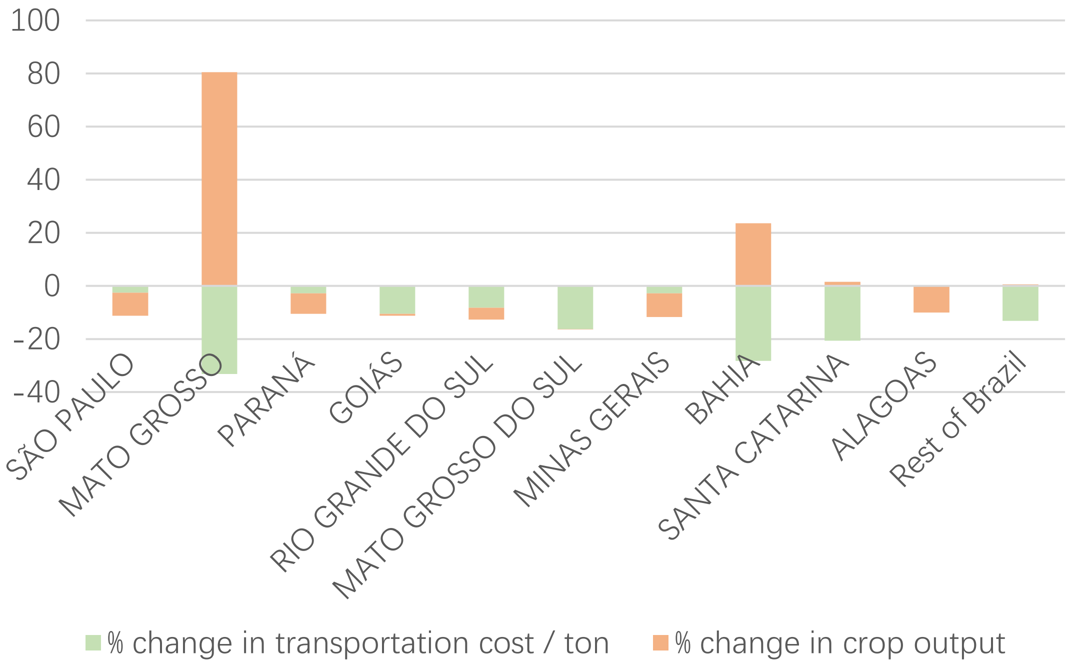

Figure 8. Decomposition of total transportation cost change (%) under SSP2

Finally, figure 9 presents the impact of crop output and cropland input change on gridded level, which captures the spatial variance within state or micro-region level due to local heterogeneity in crop production and input supply. The local level response of agriculture on transportation cost change would contribute to better understanding of the distribution of impact, and identify hotspots for further policy evaluation or intervention.

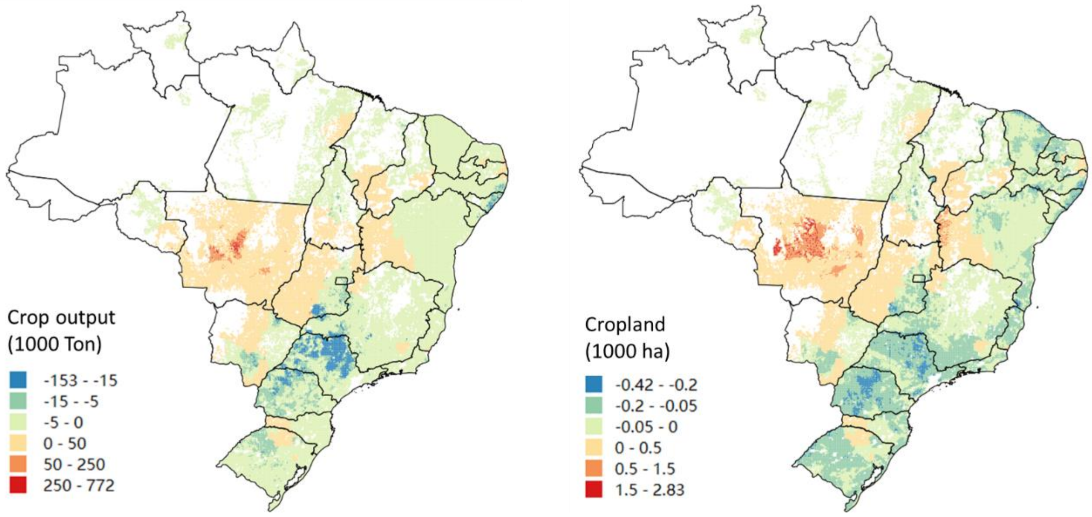

Figure 9. Spatial change due to transportation cost reduction under SSP2

4. Discussion

Results comparing with existing literature – importance to consider spillover effect

Policy implication and suggestion

5. Conclusion

Summarize research question, methodology, result and implication

Reference

Fliehr, O. 2013. *Analysis of transportation and logistics processes for soybeans in Brazil*. DE: Johann Heinrich von Thünen-Institut. Available at: https://doi.org/10.3220/WP_4_2013 [Accessed January 11, 2022].

Fliehr, Zimmer, and Smith. 2019. "Impacts of Transportation and Logistics on Brazilian Soybean Prices and Exports." *Transportation Journal* 58(1):65.

Lucich, I.M., M.G. Villena, and M.J. Quinteros. 2015. "Transportation costs, agricultural expansion and tropical deforestation: Theory and evidence from Peru." *Ciencia e investigación agraria* 42(2):3–3.

Schielein, J., G. Ponzoni Frey, J. Miranda, R.A. de Souza, J. Boerner, and J. Henderson. 2021. "The role of accessibility for land use and land cover change in the Brazilian Amazon." *Applied Geography* 132:102419.

Vera-Diaz, M. del C., R.K. Kaufmann, D.C. Nepstad, and P. Schlesinger. 2008. "An interdisciplinary model of soybean yield in the Amazon Basin: The climatic, edaphic, and economic determinants." *Ecological Economics* 65(2):420–431.

Victoria, D. de C., R.F.B. da Silva, J.D.A. Millington, V. Katerinchuk, and M. Batistella.

2021. “Transport cost to port though Brazilian federal roads network: Dataset for years 2000, 2005, 2010 and 2017.” *Data in Brief* 36:107070.

Weiss, D.J., A. Nelson, H.S. Gibson, W. Temperley, S. Peedell, A. Lieber, M. Hancher, E. Poyart, S. Belchior, N. Fullman, B. Mappin, U. Dalrymple, J. Rozier, T.C.D. Lucas, R.E. Howes, L.S. Tusting, S.Y. Kang, E. Cameron, D. Bisanzio, K.E. Battle, S. Bhatt, and P.W. Gething. 2018. “A global map of travel time to cities to assess inequalities in accessibility in 2015.” *Nature* 553(7688):333–336.