Roads, Trade, and Development: Evidence from the Agricultural Boom in Brazil

Xi He[1], Guilherme DePaula[2], and Wendong Zhang[3]

[1] Postdoctoral research associate, Department of Economics and Center for Agricultural and Rural Development, Iowa State University. xihe@iastate.edu

[2] Assistant professor, Department of Economics and Center for Agricultural and Rural Development, Iowa State University. gdepaula@iastate.edu

[3] Assistant professor, Department of Economics and Center for Agricultural and Rural Development, Iowa State University. wdzhang@iastate.edu

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Abstract: There is a need to better understand the role of trade liberalization in the impacts of road infrastructure on economic development in developing countries. We utilize a triple-differences framework combined with an instrumental variables approach to estimate the differentiated effects of road access on population, GDP per capita, and agricultural outcomes before and after the mid-1990s trade reforms for Brazilian municipalities with high and low soybean production potential. To deal with the endogeneity of road access, we use a municipality's road access to a constructed road network consisting of 1960 road network and hypothetical straight lines between major capitals as the instrument for a municipality's road access in later years. While we find road expansion leads to a significant population increase in municipalities after the trade reform, we also find that road expansion leads to higher GDP per capita in municipalities with higher soybean production potential in the agricultural frontier after the trade reform. Further analysis shows that road expansion leads to increases in soybean harvested area and yield in municipalities in the agricultural frontier with higher soybean production potential after the trade liberalization. This paper highlights the role of the export-led agricultural boom in complementing the impacts of road access on economic growth in developing countries like Brazil.

Keywords: Road access; Trade liberalization; Economic growth; Agricultural production

JEL codes: O12; O18; N56; N76; Q17

1. Introduction

The sign and magnitude of the effect of infrastructure investments on economic development remain unclear. Do infrastructure investments lead or follow economic growth? What other factors could also influence the economic returns of infrastructure investments? Although several economic studies have found that better road access leads to economic growth (Donaldson and Hornbeck, 2016; Storeygard, 2016; Donaldson, 2018; Bird, J., & Straub, 2020), other recent studies have found no evidence that improvements in road access increase income in developing countries (Banerjee, Duflo, and Qian, 2020; Asher and Novosad, 2020). Banerjee, Duflo, and Qian (2020) found that proximity to transportation networks did not affect per capita GDP growth in the two decades after China opened its economy to trade. The authors highlighted the importance of factor mobility in mediating the infrastructure effect on development. Asher and Novosad (2020) examined the economic impacts of the large-scale program that provided universal access to paved roads in rural India. The authors found that the program had only a small impact on agricultural investments and consumption. There is a need to better understand why road infrastructure has no impact on economic growth in some countries and the associated complementary policies and factors that could activate the beneficial impacts of road infrastructure on economic development.

This paper contributes to the growing literature on the infrastructure-development relationship by investigating the role of trade in mediating the effects of road access on economic growth. Brazil, one of the world's most populous countries and a major agricultural exporter, is uniquely suited for the analysis because there is a large variation in both road access and trade intensity across the country.[1] Brazil finally moved to open its trade regime in the early 1990s after a half-century of overtly inward-oriented policies (Moreira, 2009). We exploit the opening of the Brazilian economy to international markets in the mid-1990s, when the Brazilian government initiated the trade reform and started to remove some non-tariff barriers, to investigate the interaction between trade and road access on population and economic growth. In addition, the Brazilian agricultural sector boomed after the economic reforms of the 1990s, and we also study the contribution of infrastructure and trade reform to this rapid agricultural development.

[1] Brazil has a population of around 212 million in 2020, following China, India, United States, Indonesia, and Pakistan. In 2018. Brazil's total agricultural and food related exports reached $88 billion and is the second largest exporter of agricultural products after the United States (USDA, 2020).

We use a triple-differences framework combined with an Instrumental Variables approach to estimate the differentiated effect of road access in locations with high and low soybean production potential in the baseline as well as before and after trade reforms. We use a municipality's soil quality and distance to lime mines to predict its soybean production potential. The key empirical challenge in the infrastructure-development literature is the endogeneity of infrastructure investments. For example, in the Brazilian case, did public infrastructure investments contribute to the agricultural and economic growth, or did the wealthier farmers and local governments invested in road construction? We address this challenge by exploiting variation in historical road construction and creating hypothetical straight lines connecting state capitals that are close to each other. In the 1960s, the Brazilian military government implemented an infrastructure plan to protect its extensive western borders (Moran, 2016). At that point, the concern was the protection of the Amazon forest and not economic growth. Therefore, the historical road network is likely to be exogenous to economic growth after 1980. In addition, roads are also more likely to be constructed to connect state capitals and major cities (Bird, J., & Straub, 2020; Banerjee, Duflo, and Qian, 2020). To deal with the endogeneity of road access, we construct a road network that consists of straight lines connecting the centroids of nearby state capitals overlaid with the 1960 historical major roads, and then use a municipality's distance to this constructed road network as the instrument for the municipality road access to the actual road network. The validity of the instrument relies on the assumption that, conditional on the set of baseline characteristics and state-by-year fixed effects, the constructed road network affects Brazil's population, economic growth, and agricultural development only through its effects on the post-1960 transportation network.

We estimate the effects of road access on population, GDP per capita, and agricultural outcomes using a decennial municipality-level dataset from 1980 to 2010 and in 2017. We obtain geo-referenced road maps from 1960 to 2010 every ten years and in 2017 from Brazil's National Department of Transport Infrastructure (DNIT, 2020). We define municipalities' centroids and use the Euclidean distance from each municipality's centroid to the nearest road network to measure road access. For each of the five outcome years (1980, 1990, 2000, 2010 and 2017), we examine two sets of outcomes: 1) economic growth outcomes, including municipality-level population and GDP data obtained from the population census surveys (IBGE, 2020); 2) the agricultural production outcomes, which include corn and soybean harvested area, corn and soybean yield, and agricultural production value (IBGE PAM, 2020); We also test if these impacts are differentiated by a municipality's soybean production potential, which is predicted from a municipality's soil quality and distance to lime mines.

We have four major findings. First, we find that the constructed network consisting of the 1960 historical network and hypothetical straight lines connecting major state capitals is a strong predictor of road access in later periods. We are encouraged by the power of the instrument in identifying road effects. Second, we find a positive effect of road access on population across regions after the trade reform, and the magnitude of the impacts vary across their agricultural development and soybean production potential. Third, we find a statistically significant positive impact of road access on GDP per capita in municipalities with higher soybean production potential after the trade reform. Since most of the growth in agricultural exports post-reform happened in the agricultural frontier in the Central-West region and the Cerrado biomes excluding the Caatinga biomes (See Figure A1 for the geographical classification) (The share of soybean harvested area in the Central West area increased from 13.6% in 1980 to 45.7% in 2017), this result suggests a significant interaction effect between trade and infrastructure. Fourth, we find a positive effect of road access on soybean acreage and yields in locations with high soybean production potential after the trade reform. This result indicates that infrastructure investments in part enabled the export-led agricultural development in the agricultural frontier.

This paper relates to two strands of literature. First, this paper relates to the extensive infrastructure-development literature by shedding light on the role of trade in enabling an export-led economic boom in a developing country (Donaldson and Hornbeck, 2016; Storeygard, 2016; Donaldson, 2018; Bird, J., & Straub, 2020; Banerjee, Duflo, and Qian, 2020; Asher and Novosad, 2020). The Brazilian economy's unique historical infrastructure development and economic transition allow us to mitigate the road access endogeneity problem. Our results suggest that the cost savings from Brazil's road infrastructure might have just tilted the economic incentives towards transforming a large region of cattle ranches into a growing agricultural frontier and export hub. Second, this paper relates to the extensive literature on the relationship between road infrastructure, agricultural development, and deforestation in Brazil (Pfaff et al., 2007; Richards et al., 2014; Bebbington et al., 2018). While this literature focuses on quantifying the impacts of road investment on deforestation, our paper sheds light on this question from the angle of agricultural development and the role trade liberalization plays in this process. We provide evidence that road infrastructure and trade together created incentives for agricultural development, and therefore deforestation. It would be important to account for both road investment and trade liberalization in explaining Brazil's deforestation.

The rest of the paper proceeds as follows. Section two introduces the history of road infrastructure and market liberalization in Brazil. Section three describes the identification methodology, followed by data sources and summary statistics in section four. Section five presents the empirical results. The last section concludes.

2. Background on Road Infrastructure, Trade Liberalization, and Economic Growth in Brazil

2.1 Road Infrastructure

Brazil's transportation infrastructure development closely relates to its economic history characterized by the shifting dominance of different high-value commodities, including timber, sugarcane, gold, and coffee (World Bank, 2008).[2] During Brazil's early colonial period until the seventeenth century, timber exploitation was a large part of the economy, and transportation primarily relied on animal tracks and primitive roads. From the seventeenth to the nineteenth century, when sugarcane and gold were the primary goods to be transported, several major inland waterways were developed to connect Minas Gerais, a large inland state in southeastern Brazil, with Rio de Janeiro, a major coastal port city in the south. In the late eighteenth century, coffee growers financed railroads in the coffee region of the province of São Paulo (Lamounier, 2000). Between 1850 to 1950, several critical roads and railroads that serve as Brazil's modern transportation determinants were constructed in the Southeast and Northeast coastal areas. There were new connections between State capitals and the Atlantic coast in the 1950s, and the national highway system was first mentioned when the location of the new capital Brasília was decided. In the 1960s, several new roads connected hinterland main urban centers, linking Brasília with Brazil's extremes in eight directions: north, northeast, east, southeast, south, southwest, west, and northwest. The government also introduced several important inter-state highways in the Legal Amazon in the 1960s and 1970s. For example, the BR-364 opened in the 1960s is the first

[2] Castro (2004) provides an excellent summary of Brazil's road expansion since the 1870s.

main road connecting the Amazon basin and the rest of Brazil, and it played an important role in the transportation of agricultural and livestock production in the states of Rondônia, Mato Grosso, and Goiás, for both domestic consumption and export.

With the growing competitiveness of Brazil's agricultural exports since its trade liberalization in the 1990s, the Brazil government and other multi-national investment companies have been investing in the road infrastructure to transport the soybeans and other agricultural products from the major traditional producing states in the South and the agricultural frontier in the Central West area to coastal ports in the northeast and southeast (Richards et al., 2014). However, with growing concerns on deforestation, notably in the Amazon area, there are persistent policy debates on road infrastructure projects due to their conflicting impacts on economic development and deforestation (Richards et al., 2014; Vilela et al., 2020).

2.2 Trade Reform in the 1990s and Agricultural and Economic Growth since the 2000s

Brazil adopted a restricted trade regime rooted in import substitution and national industry protection throughout the late 1980s. In 1988, the Brazilian government initiated trade reform and started to remove some non-tariff barriers. It then signed the Mercosur agreement (Southern Common Market) with Argentina, Paraguay, and Uruguay in 1991.[3] Mercosur was launched by the Treaty of Asuncion, which asked for the implementation of a common market until 1995. Brazil's average nominal tariff across all commodities decreased from 40.4% in 1990 to 12% in 1996, and further lowered to 11.1% in 2005 (Castilho et al., 2012).

After the trade reform, Brazil's exports grew from $31 billion in 1990 to $239 billion in 2019, with agricultural exports increased from $9.38 billion in 1990 to $88 billion in 2019 (IBGE, 2020). The share of agricultural exports also grew steadily from 30% to 40% during this period. Agricultural exports, especially soybean exports, play a vital role in Brazil's economic growth (Arias et al., 2017). U.S. and Brazil exported around 80% of the world's soybeans in 2019. Brazil surpassed the U.S. and became the world's largest soybean exporter in 2014, with its soybean exports reached around $33 billion in 2018, about twice of U.S. soybean exports of $17

[3] Venezuela joined Mercosur as a fifth member in2012, but was suspended in late 2016.

billion.[4] Brazil's export-led agricultural development also promoted the development of the agricultural frontier in the central west, especially in the state of Mato Grosso.

The vast spatial and temporal variation in road expansion, economic and agricultural development makes Brazil an ideal setting for investigating the interactive impacts of road infrastructure and trade reforms on agricultural growth and economic development.

3. Empirical Framework

3.1 Basic Model

The basic model we use to investigate the impact of road access on economic development is:

$$ln\, Y_{ist} = \alpha_0 + \beta_0\, ln\, R_{ist} + \gamma X_{is} + \theta_{st} + \varepsilon_{ist}, \qquad (1)$$

where $i, s, and\ t$ denotes municipality, state, and year, respectively. $ln\, Y_{ist}$ denotes the natural logarithm of outcomes of interest, including population and GDP per capita at the municipality level. $ln\, R_{ist}$ is the natural logarithm of the straight-line distance to the nearest existing major road network for the centroid of municipality i in state s in year t. It is worthy of attention that the major roads considered in this paper only include paved state and federal roads and unpaved or municipality-level roads are excluded. Figure 1 presents the major road network in 1960 and 2017. X_{is} is a vector of municipality-level controls, including municipality land size and distance to their respective state capitals. We also include state-by-year fixed effects, θ_{st}, to control for systematic macro differences across states over time. ε_{ist} is an error term. We cluster standard errors at the municipality level. If road access expansion is beneficial for population and GDP per capita, then $\beta_0 < 0$.

To investigate if trade liberalization affects the impact of road access on population and GDP per capita, we add an interaction term of $ln\, R_{ist}$ and $Post_t$ and expand equation (1) into a Difference-in-Differences (DID) framework:

$$ln\, Y_{ist} = \alpha_0 + \beta_1\, ln\, R_{ist} + \beta_2\, ln\, R_{ist} * Post_t + \gamma X_{is} + \theta_{st} + \varepsilon_{ist}, \qquad (2)$$

where $Post_t$ is a dummy variable to capture trade liberalization. It equals 1 if $t \geq 2000$; otherwise, it equals 0. The coefficient of the interaction term, β_2, captures whether the impact

[4] The U.S.-China trade conflict that started in 2018 further caused China to shift its soybean sources from the U.S. to South American countries (Cowley, 2020).

of road access on development is different before and after the trade reform. If $\beta_2 < 0$, the beneficial impact of road access on population and GDP is larger in magnitude after the trade reform.

However, equation (2) cannot test the potential differentiated impacts of trade liberalization across municipalities with high and low soybean production potential. To exploit the significant soybean production potential across municipalities, we classify municipalities into high and low soybean production potential groups based on their soil characteristics and distance to lime mines given that lime is an important input to correct the soil pH. We then expand equation (2) into the following triple-difference specification to test if the impact of road access on economic development is stronger in municipalities with higher soybean production potential after the trade reform:

$$ln\, Y_{ist} = \alpha_0 + \beta_0\, ln\, R_{ist} + \beta_1 Post_t + \beta_2\, ln\, R_{ist} * Post_t + \beta_3\, ln\, R_{ist} * Pot_{is} + \beta_4 Post_t * Pot_{is} + \beta_5\, ln\, R_{ist} * Post_t * Pot_{is} + \gamma X_{is} + \theta_{st} + \varepsilon_{ist}, \quad (3)$$

Pot_{is} is a dummy variable indicating whether a municipality is classified as having high soybean production potential. The coefficient of the triple interaction term $ln\, R_{ist} * Post_t * Pot_{is}$ captures whether the interaction effect of road access and trade reform is different for municipalities with higher high soybean production potential. If $\beta_5 < 0$, the beneficial effect of road access after trade access on population and GDP per capita is stronger for municipalities with higher high soybean production potential.

Given that agricultural production and exports make significant contributions to Brazil's economic growth, we also test the impacts of road access on Brazil's agricultural outcomes, including harvested acreage and yield of soybeans and corn. The empirical specifications are the same as in equation (3) expect the dependent variables are agricultural-related outcomes.

3.2 Instrument Variables Strategy

OLS estimates of impacts of road access might be biased due to the endogeneity of road access arising from omitted variables and reverse causality. For example, there are likely unobserved variables, such as geographical variables, that affect a municipality's road expansion and economic development simultaneously or cause road infrastructure to be allocated to regions where they would have more significant economic impacts (Coşar and Demir, 2016; Asher and

Novosad, 2020). Alternatively, if a more developed municipality is more likely to invest in road infrastructure, OLS estimates are also biased.

To deal with the endogeneity of road access, we use an IV approach by exploiting variation in historical road construction in 1960 and hypothetical straight lines connecting state capitals in Brazil. Specifically, we construct a road network that consists of straight lines connecting the centroid of adjacent state capitals overlaid with the 1960 roads. We then use a municipality's distance to this constructed road network as the instrument for this municipality's road access to existing road network in later periods. The validity of this identification strategy relies on the assumption that, conditional on a set of baseline characteristics and state-by-year fixed effects, the constructed road network affects Brazil's agricultural development and economic growth only through its impacts on the post-1960 transportation network. In the 1960s, the Brazilian military government implemented an infrastructure plan to protect its extensive western borders. At that point, the concern was the protection of the Amazon forest and not economic growth. Therefore, the historical road network is likely to be exogenous to economic growth.

The two maps in Figure 1 show the hypothetical straight lines and the federal and state road infrastructure in 1960 and 2017, respectively. In 1960, road infrastructure was primarily located in the South and Southeast. In 2017, road infrastructure spread over Brazil except for the Legal Amazonia.

To check that a municipality's distance from the constructed road network is indeed a strong predictor of the municipality's road access in later years, we estimate the correlation between distance to the constructed road network and road access in later years using the following model:

$$ln\, R_{ist} = \alpha_0 + \beta\, ln\, R_{is1960} + \gamma X_{is} + \theta_{st} + \varepsilon_{ist}, \quad (4)$$

where $ln\, R_{is1960}$ denotes the logarithm of distance to the constructed road network. Other notations have the same meaning as in equation (1). A positive β indicates that higher road access in 1960 leads to higher road access in later years.

3.3 Dynamic Impacts of Trade Reform

The DID and DDD models specified in equations (2) and (3) cannot capture the dynamic impacts of road access and trade liberalization. Therefore, to explore the dynamic impacts of road access over time, we expand equations (2) and (3) into:

$$ln\,Y_{ist} = \alpha_0 + \sum_{t=1}^{T} \beta_t \, ln\,R_{ist} + \gamma X_{is} + \theta_{st} + \varepsilon_{ist}, \tag{5}$$

$$ln\,Y_{ist} = \alpha_0 + \sum_{t=1}^{T} \beta_{t0} \, ln\,R_{ist} + \sum_{t=1}^{T} \beta_{t1} \, ln\,R_{ist}\,Exp_{is} + \gamma X_{is} + \theta_{st} + \varepsilon_{ist}, \tag{6}$$

$t = 1, \ldots, 5$ denotes the five study periods: every ten years from 1980 to 2010 and 2017.

β_t in equation (5) is a set of time-variant coefficients that capture the dynamic impacts of road access in the five study periods: every ten years from 1980 to 2010 and 2017. β_{t1} in equation (6) is a set of time-variant coefficients that capture the dynamic impacts of road access in municipalities with higher soybean production potential. Other notations have the same meanings as in equation (2). Note that we also use the instrument to deal with the endogeneity of road access in estimating equations (5) and (6).

4. Data and Summary Statistics

4.1 Data Sources

To investigate the impacts of road infrastructure on economic development, we compile a municipality-level dataset from multiple sources every ten years from 1980 to 2010 and 2017. The number of municipalities in Brazil increased from 2,767 in 1960 to 5,564 in 2010. To account for municipality border changes, we adjust data in earlier periods to maintain the 2010 municipality definitions. We obtain population and GDP data from the population census surveys from IBGE (IBGE, 2020). We obtain municipality-level data on corn and soybean harvested area, corn and soybean yield, total agricultural area, and agricultural production from the Instituto Brasileiro de Geografia e Estatística, Produçao Agrícola Municipal (IBGE PAM, 2020).

To construct each municipality’s road access, we collect geo-referenced road maps from 1960 to 2010 every ten years and in 2017 are from Brazil’s National Department of Transport Infrastructure (DNIT, 2020). We define the centroids of municipalities and measure a municipality’s road access as the distance from its centroid to its nearest major road network, which only includes paved federal and state roads.

Given that many states in the Legal Amazonia have relatively low population densities and economic activities, we exclude six states: Acre, Amazonas, Amapa, Para, Rondonia, and Roraima, from the analysis. We also exclude municipalities in which state capitals reside from the analysis for endogeneity concerns: most historical roads in the 1960s intended to connect state capitals, and therefore, the endogeneity problems for state capitals are severe. Our final sample is a balanced panel of 5,140 municipalities in 1980, 1990, 2000, 2010, and 2017.

4.2 Summary Statistics

Table 1 summarizes the main variables in the analysis. In 1960, average distance from a municipality's centroid to its nearest existing major road network is 182.9km, average distance from a municipality's centroid to its nearest actual road and constructed straight lines is 91.8km. In 2017, average distance from a municipality's centroid to its nearest road is 15.7 km, indicating significant road access expansion from 1960 to 2017. Figure A1 in the Appendix shows the kernel density distribution of municipalities' average distance to their nearest major road network over time. While municipalities on average had higher road access over time, their road access improved slower over time.

From 1980 to 2017, average municipality-level population increased by around 25% from 22,899 to 28,650, average GDP per capita increased by around seven times from 3,565 Reals to 22,111 Reals, agricultural production value increased by around fourfold, and the share of agriculture in GDP decreased from 29% to 14%. Over the same period, average soybean harvested area increased by about three times from 1,555 hectares to 5,902 hectares, and average corn harvested area grew at a slower pace from 2,085 hectares to 3,077 hectares. Both soybean and corn yield has more than quadrupled over the study period.

To preview the relationship between road access, trade, population, GDP per capita, and agricultural outcomes, we present the summary statistics separately for municipalities with higher and lower road access before and after the trade reform in the mid-1990s in Table 2. We define municipalities with higher and lower road access using the median road access in 1960, 108.4 Km. Columns (6), (8), and (10) show that, compared with municipalities with lower road access in 1960, municipalities with better road access in 1960 grew faster in terms of population yet lower in terms of GDP per capita and agricultural-related outcomes, including agricultural production, soybean/corn harvested area, corn/soybean yield, and total harvested area. These patterns indicate that municipalities with lower road access in 1960 experienced faster agricultural and economic growth but lower population growth than their counterparts with higher road access in 1960.

Figure 2 shows the kernel density distribution of population and GDP per capita for municipalities with higher and lower road access in 1960 before and after the trade reform. Other than the pattern that both population and GDP per capita increased after trade reform, there is also evidence that population becomes more dispersed.

5. Empirical Results

5.1 Validity of Instrument Constructed from the Constructed Road Network

We first check the validity of using the distance to the constructed road network, which consists of the 1960 road network overlaid with hypothetical straight lines between state capitals close to each other, as the instrument for distance to the actual road network in later years (every ten years from 1980 to 2010 and 2017). Table 3 presents the estimation results of equation (4), which tests the correlation between municipalities' distance to the constructed road network and distance to the nearest major road in later years. Considering Brazil is a vast country with quite different socioeconomic and geographical conditions across regions, we separately present results for arid regions, which include the Pantanal and Caatinga biomes as shown in Figure A1 in the appendix, and nonarid regions. Within the nonarid regions, we also separately present the results for the agricultural region, which includes the Cerrado biomes, south, and central-west region excluding the Caatinga biomes, the agricultural frontier in the central-west region and the Cerrado biomes excluding the Caatinga biomes, and nonagricultural areas. Figure A1 in the Appendix presents the geographical classifications of the six biomes and five regions in Brazil and the subsamples in the analysis. We include baseline controls, including municipality size and distance to state capitals, and state-by-year fixed effects in all specifications. We cluster standard errors at the municipality level.

The results in table 3 show statistically positive correlations between distance to the constructed road network and distance to the actual road network in later periods. The correlation is larger in magnitude for nonarid areas than for arid regions, larger for agricultural regions than for nonagricultural regions, and is largest for municipalities in the agricultural frontier. The distance to state capitals is also positively correlated with a municipality's road access in later years. Overall, the results in Table 3 show the constructed instrument based on roads in 1960 and hypothetical lines connecting state capitals is a strong predictor of road access in later periods.

5.2 Population and GDP per Capita: DID Combined with IV

We first present the estimation results of equation (2), in which we use a DID combined with an IV approach to test the impacts of road access on population and GDP per capita before and after the trade reform. Table 4 presents the OLS and IV estimation results for the full sample, municipalities in nonarid regions, and municipalities in the arid regions. For simplicity, we only report the coefficients of β_1 and β_2. The F-statistics for the full sample and nonarid sample are large than 10, but the F-statistics for the arid sample is 0.78, indicating that the instrument is strong in nonarid regions but not in arid regions, which is consistent with the weak correlation between distance to constructed road network and distance to actual road network in later years as shown in Column (3) Table 3.

In terms of population, IV results in Panel A column (4) show that distance to major roads has a statistically significant negative impact on population in municipalities located in nonarid areas. This negative impact becomes larger after the trade reform, and the increase is also statistically significant. IV results in column (6) show distance to major roads has no statistically significant impact on population for municipalities in arid areas. Overall, the results in panel A show that road access significantly increases population in nonarid areas, and this impact become significantly larger after trade reform.

In terms of GDP per capita, IV results in Panel B column (4) show that distance to major roads has a statistically significant negative impact on GDP per capita for municipalities in nonarid areas. This negative impact becomes significantly smaller after the trade reform at the 5% level. IV results in column (6) show that distance to major roads has a statistically significant negative impact on GDP per capita for municipalities in arid areas, and this impact is not statistically different before and after the trade reform. Overall, results in panel B show that road access significantly increases population and GDP in nonarid areas after the trade reform. Quantitatively, a 1% decrease in a municipality's distance to its nearest road network increases its population by 0.357% and decreases GDP per capita by 0.045% after the trade reform.

Given that agriculture plays a significant role in Brazil's economic growth, we further divide the nonarid areas into the agricultural area, the agricultural frontier, and nonagricultural areas (See Figure A1 in the appendix for classification). The results for the three sub-samples in Table 5 show significant impacts of road access on population increase for agricultural areas, agricultural frontiers, and nonagricultural regions after the trade reform. Panel B shows that the beneficial impact of road access on GDP per capita after trade reform only exists for municipalities in the agricultural frontier and not for municipalities in nonagricultural areas.

Overall, results from DID combined with IV show that road access leads to a significant population increase in nonarid areas, and the impact on the population is larger in magnitude after the trade reform. In addition, better road access leads to a significant decrease in GDP per capita in nonarid areas after the trade reform, and this impact is driven by nonagricultural areas.

5.3 Population and GDP: Triple-Difference Combined with IV

Given that trade reform's impact largely depends on a municipality's export potential, we further use equation (4) to explore whether the interactive impacts of road access and trade reform are larger for municipalities with high soybean production potential.

Table 6 presents estimation results. We focus on the coefficients of the interaction term *logarithm of distance to nearest road network*Post trade reform*High soybean production potential*. A negative coefficient indicates better road access leads to more population (higher GDP per capita) in municipalities with higher soybean production potential after trade reform. Panel A shows that better road access has no statistically significant impact on population in municipalities with higher soybean production potential in nonarid areas after the trade reform. Panel B shows that better road access leads to higher GDP per capita population in municipalities with higher soybean production potential in nonarid areas, and in particular the agricultural frontier, after the trade reform.

5.4 Agricultural Outcomes: Triple-Difference combined with IV

Given the findings that road access leads to GDP per capita growth in the agricultural frontier after the trade reform, we test the interactive impacts of road access, trade reform, and export intensity on Brazil's agricultural development. We pay special attention to Brazil's soybeans and corn.

Table 7 presents the estimation results of equation (4) with agricultural outcomes, including soybean harvested area and soybean yield. We also separately present the results for the full sample, nonarid sample, arid sample, agricultural regions, agricultural frontier, and nonagricultural areas. Results in column (4) show that road access leads to more soybean harvested area and soybean yield in municipalities with higher soybean production potential in nonarid areas after trade reform. In addition, this impact is more likely for municipalities in the agricultural frontier, which is the hub of soybean exports.

Table A1 in the appendix presents the estimation results of equation (4) with agricultural outcomes, including corn harvested area and corn yield. There is clear evidence that road expansion after the trade reform leads to lower corn harvested area and corn yield in the municipalities with higher soybean production potential in the agricultural frontier and agricultural area. Together with the finding in Table 7, there is evidence that road expansion after the trade reform leads to soybean harvested area/yield increase and leads to corn harvested area/yield decrease in municipalities with high soybean production potential in agricultural areas.

6. Conclusions

Current studies have mixed findings on the beneficial impacts of road infrastructure on economic development. This paper explores the role of trade liberalization in mediating the impacts of road infrastructure on development in Brazil. Brazil's continuing efforts in improving its road network (for example, Brazil planned to extend the BR-163 highway from the central soybean-producing regions north to the border with Suriname) and its trade liberalization started in the 1990s provides a good setting to investigate the interactive impact of transportation infrastructure and trade liberalization in promoting Brazil's agricultural and economic development. We compile a municipality-level dataset covering 5,140 municipalities in 1980, 1990, 2000, 2010, and 2017. To deal with the endogeneity of a municipality's distance to major roads, we construct a road network consisting of 1960 historical roads and hypothetical lines linking state capitals. We use a DDD framework combined with the IV strategy to examine the impacts of road access on population and GDP per capita, and test if these impacts are different in municipalities with lower and higher soybean production potential after the trade reform. Given that agricultural exports make a significant contribution to Brazil's development, we also test the impacts of road access on agricultural outcomes.

We have several major findings. First, we estimate a positive effect of road access on the population in nonagricultural municipalities after the trade reform. Second, we find a statistically significant positive impact of road access on GDP per capita in the agricultural frontier with higher soybean production potential after the trade reform. Since most of the growth in agricultural exports post-reform happened in the frontier, this finding suggests a significant interaction effect between trade and infrastructure. Finally, we find a positive effect of road access on soybean acreage and yields in locations with high soybean production potential after the trade reform. This finding indicates that infrastructure investments in part enabled the export-led agricultural development in the agricultural frontier.

This paper contributes to the current literature by emphasizing the role of infrastructure in enabling an export-led economic boom in a developing country. The unique historical infrastructure development and economic transition of the Brazilian economy allow us to mitigate the road access endogeneity problem. Our results suggest that the cost savings from the road infrastructure in Brazil might have just tilted the economic incentives towards transforming a large region of cattle ranches into a growing agricultural frontier and export hub.

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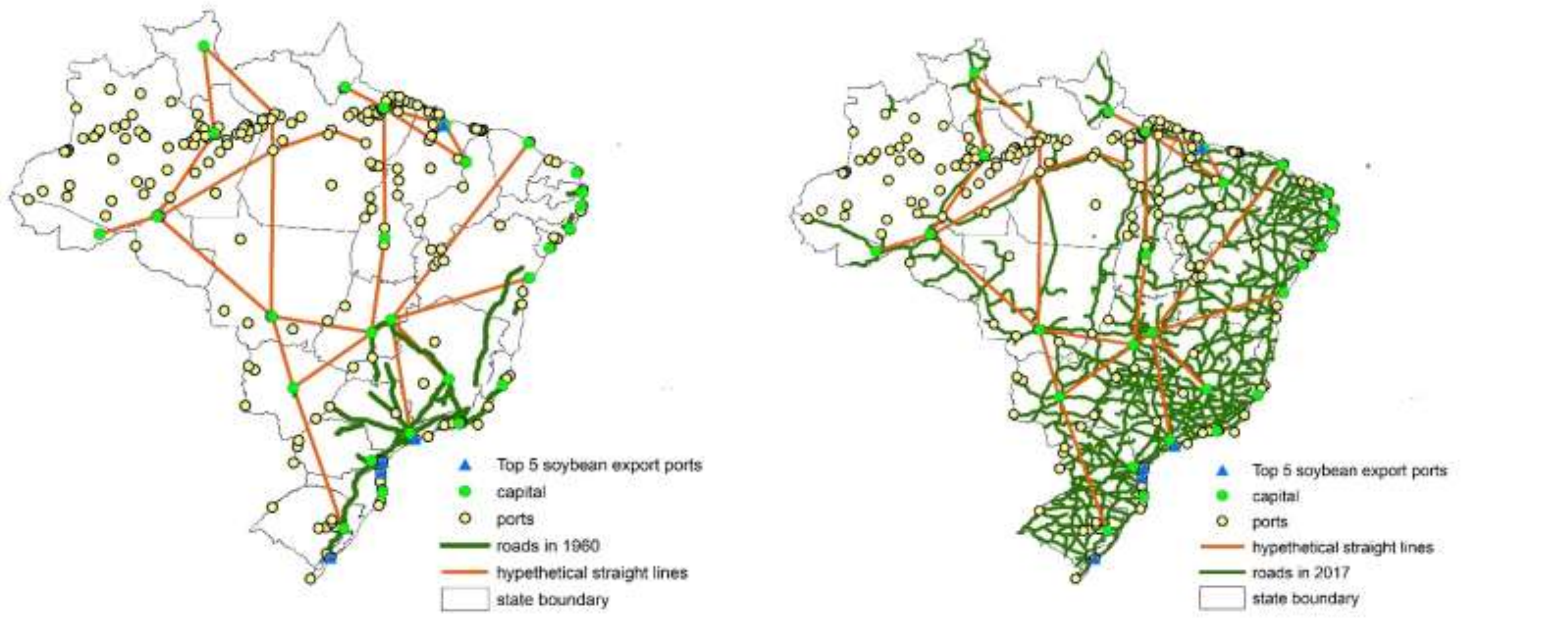
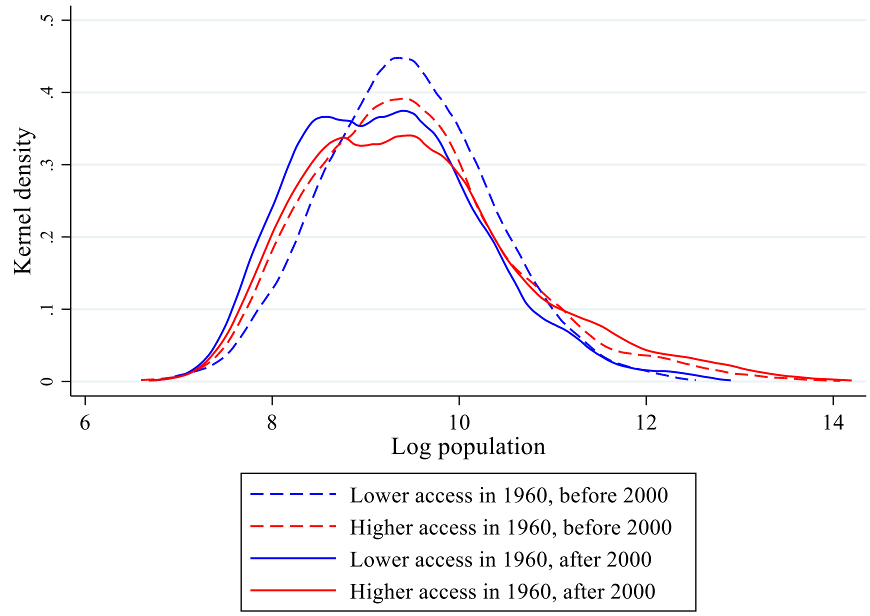
Figure 1. Hypothetical Lines Linking State Capitals and Major Road Network in 1960 and 2017.

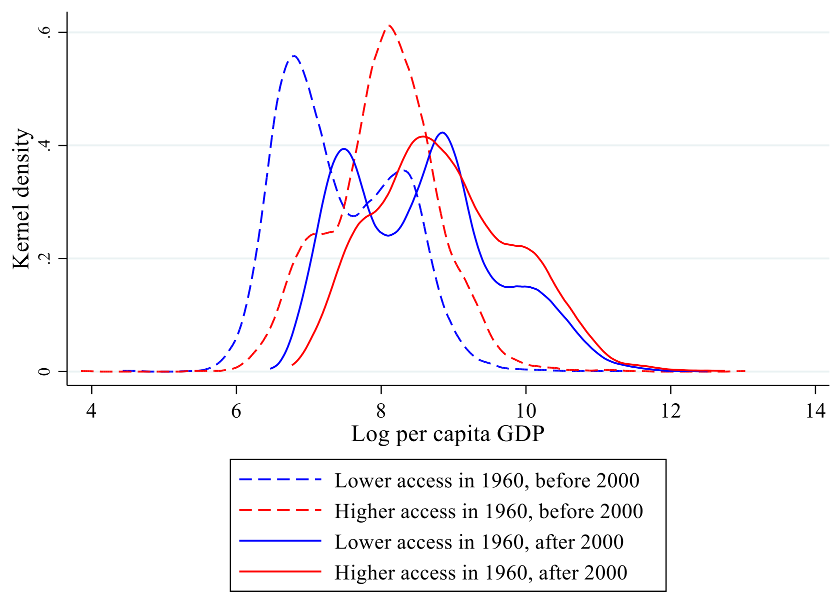


Panel A: Hypothetical Lines and Road Infrastructure in 1960 Panel B: Hypothetical Lines and Road Infrastructure in 2017

Notes: The two figures show the hypothetical lines that connect major state capitals and road infrastructure in 1960 and 2017, respectively. The orange lines are the hypothetical lines connecting major state capitals. Green lines are the existing paved federal and state roads. Green dots denote state capital. Yellow dots represent major ports. We obtain shapefiles of road infrastructure from Brazil's National Department of Transport Infrastructure (DNIT, 2020).

Figure 2. Density Distribution of Municipality-level Population and GDP per Capita for Municipalities with High and Low Road Access in 1960 Before and After 2000.





Notes: The two figures show the distribution of population and GDP per capita for municipalities with higher and lower road access in 1960 before and after the trade reform in the mid-1990s. We use their median road access in 1960, 108.4 Km, to define municipalities with higher and lower road access.

Table 1. Summary Statistics of Main Variables

	Entire sample	1980	2000	2017
Panel A: Road access				
Distance to 1960 road (Km)	182.89	182.89	182.89	182.89
	(203.30)	(203.32)	(203.32)	(203.32)
Distance to constructed hypothetical straight lines and the 1960 road (Km)	91.78	91.78	91.78	91.78
	(82.47)	(82.48)	(82.48)	(82.48)
Distance to state capital (Km)	222.66	222.66	222.66	222.66
	(126.71)	(126.72)	(126.72)	(126.72)
Distance to nearest road (Km)	21.47	33.92	19.41	15.68
	(31.30)	(51.71)	(24.95)	(16.06)
Panel B: Population and GDP				
Total population (person)	25491.50	22899.13	23732.11	28650.59
	(59405.25)	(44766.28)	(56747.53)	(69922.90)
GDP per capita (Real in 2000)	8177.74	3565.11	4115.02	22111.16
	(13346.50)	(8307.57)	(4736.59)	(20832.98)
Panel C: Agricultural outcomes				
Soybean harvested area (Hectares)	3230.47	1555.90	2523.39	5902.45
	(16645.15)	(7723.11)	(13066.35)	(25429.00)
Soybean yield (Kg per hectare)	709.99	320.32	617.83	1314.36
	(1199.67)	(692.86)	(1029.82)	(1636.84)
Corn harvested area (Hectares)	2322.17	2085.83	2118.66	3077.95
	(8279.55)	(4862.02)	(4451.70)	(14873.56)
Corn yield (Kg per hectare)	2183.88	945.09	2014.71	4556.30
	(2781.72)	(993.55)	(1420.12)	(4517.07)
Total harvested area (Hectares)	4905.51	3641.72	4642.05	6819.27
	(18303.61)	(10663.07)	(16255.39)	(26441.70)
Agricultural production (Real thousand reals in 2000)	20446.12	12079.44	6542.08	48462.55
	(75647.09)	(21831.00)	(15951.33)	(144754.75)
Share of agricultural production in GDP	0.21	0.29	0.13	0.14
	(0.36)	(0.59)	(0.15)	(0.21)
Number of observations	25,700	5,140	5,140	5,140

Notes: The samples include 5,140 municipalities in Brazil in 1980, 1990, 2000, 2010, and 2017. We exclude municipalities in six states: Acre, Amazonas, Amapa, Para, Rondônia, Roraima, and municipalities in which state capitals reside from the analysis.

Table 2. Summary Statistics of Municipalities with Lower and Higher Road Access Before and After Trade Reform

	Municipalities with lower road access in 1960		Municipalities with higher road access in 1960		Municipalities with lower road access in 1960		Municipalities with higher road access in 1960			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Before 2000	After 2000	Before 2000	After 2000	Difference between (3) and (1)	Growth rate from (1) to (3)	Difference between (4) and (2)	Growth rate from (2) to (4)	Difference between (7) and (5)	Difference between (8) and (6)
Total population (Person)	19289.57	17866.53	27687.54	33977.98	-1423.04	-7.38%	6290.44	22.72%	7713.48	30.10%
	(22500.55)	(28120.91)	(63322.03)	(83391.26)						
GDP per capita (in 2000 Real)	2393.43	9179.48	4196.88	12031.11	6786.05	283.53%	7834.23	186.67%	1048.18	-96.86%
	(2984.90)	(12787.31)	(7989.71)	(17051.36)						
Total agricultural production (in 2000 Thousand Real)	10256.53	29540.39	10107.60	22338.25	19283.86	188.02%	12230.65	121.00%	-7053.21	-67.01%
	(20828.40)	(115325.58)	(17464.11)	(62101.01)						
Soybean harvested area (Hectares)	2706.61	6533.16	1002.25	1998.59	3826.55	141.38%	996.34	99.41%	-2830.21	-41.97%
	(11679.10)	(27678.93)	(4502.58)	(8343.94)						
Corn harvested area (Hectares)	2338.47	3489.05	1837.74	1561.54	1150.58	49.20%	-276.2	-15.03%	-1426.78	-64.23%
	(5394.78)	(13611.88)	(3797.33)	(4412.26)						
Soybean yield (Kg per hectare)	319.95	993.40	402.98	893.14	673.45	210.49%	490.16	121.63%	-183.29	-88.85%
	(688.50)	(1396.31)	(760.61)	(1368.28)						
Corn yield (Kg per hectare)	733.66	2720.44	1313.27	3160.15	1986.78	270.80%	1846.88	140.63%	-139.9	-130.17%
	(987.83)	(3234.81)	(1020.75)	(3290.94)						
Total harvested area (Hectares)	5045.08	8307.41	2839.98	3066.97	3262.33	64.66%	226.99	7.99%	-3035.34	-56.67%
	(14633.15)	(29312.83)	(7128.16)	(9978.07)						
Number of observations	4,926	7,389	5,354	8,031						

Notes: This table summarizes the main variables for municipalities with lower and higher road access before (1980 and 1990) and after trade reform (2000, 2010, and 2017). We use the median distance to the constructed road network, 108.4 Km, to define municipalities with low and high road access. Columns (5) and (6) report the absolute and percent difference of variables in municipalities with lower and higher road access before trade reform. Columns (7) and (8) report the absolute and percent difference of variables in municipalities with lower and higher road access after trade reform.

Table 3. Impact of Distance from Constructed Road Network on Distance from Actual Road Network in Later Years.

	Full sample	Non-arid regions	Arid regions	Agricultural regions	Agricultural frontier	Non-agricultural regions
	(1)	(2)	(3)	(4)	(5)	(6)
Log of distance to constructed road network	0.204***	0.237***	0.044	0.169***	0.264***	0.243***
	(0.014)	(0.015)	(0.036)	(0.020)	(0.029)	(0.019)
Municipality land size	0.057***	0.053***	0.027	0.018	0.066**	0.058***
	(0.014)	(0.016)	(0.032)	(0.020)	(0.027)	(0.020)
Log of distance to state capital	0.110***	0.107***	0.096*	0.087***	0.090*	0.111***
	(0.021)	(0.023)	(0.050)	(0.031)	(0.049)	(0.029)
Constant	0.843***	0.786***	1.766***	1.444***	1.016***	0.602***
	(0.113)	(0.130)	(0.277)	(0.189)	(0.275)	(0.143)
State-by-year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.212	0.250	0.111	0.244	0.279	0.181
Number of observations	25,700	20,165	5,535	11,185	5,735	14,515

Notes: This table presents the estimation results of regressing the log of distance to existing road network on the log of distance to the constructed road network in 1960 (the overlay of 1960 road network and the hypothetical straight lines connecting state capital) and a set of baseline controls. We include state-by-year fixed effects in all specifications. We classify agricultural regions as the combination of Cerrado biomes and the central-west region. Agricultural frontier includes the Cerrado biomes. We also define the northeast region and Caatinga biomes as arid regions and the rest as nonarid areas. We cluster the standard errors at the municipality level. *, **, and *** denotes significant level at 10%, 5%, and 1% respectively.

Table 4. Impacts of Road Access on Population and GDP per Capita: Difference-in-differences Combined with the Instrument Variables Approach.

	Full		**Nonarid areas**		**Arid areas**	
	OLS	IV	OLS	IV	OLS	IV
Dependent variable: logarithm of population						
Logarithm of distance to nearest road network	-0.179***	-0.346***	-0.209***	-0.360***	-0.108***	-0.561
	(0.012)	(0.052)	(0.014)	(0.052)	(0.020)	(0.415)
*Logarithm of distance to nearest road network*Post trade reform*	-0.053***	-0.357***	-0.049***	-0.357***	-0.032**	-0.314
	(0.008)	(0.044)	(0.010)	(0.045)	(0.015)	(0.469)
R-squared	0.452	0.322	0.443	0.332	0.535	0.026
First-stage F-statistics		92.388		103.526		0.779
Number of observations	23,463	23,463	18,335	18,335	5,128	5,128
Dependent variable: logarithm of GDP per capita						
Logarithm of distance to nearest road network	-0.109***	-0.308***	-0.108***	-0.257***	-0.085***	-0.733*
	(0.007)	(0.031)	(0.008)	(0.030)	(0.011)	(0.432)
*Logarithm of distance to nearest road network*Post trade reform*	0.048***	0.075***	0.041***	0.045*	0.046***	0.200
	(0.007)	(0.025)	(0.008)	(0.026)	(0.010)	(0.248)
R-squared	0.644	0.593	0.505	0.465	0.595	0.407
State-by-year fixed effects	Y	Y	Y	Y	Y	Y
First-stage F-statistics		92.404		103.557		0.781
Number of observations	23,458*	23,458	18,332	18,332	5,126	5,126

Notes: This table presents the OLS and IV estimation result of equation (2). We obtain the IV results by instrumenting distance to the nearest road with distance to the constructed road network. We include state-by-year fixed effects and cluster standard errors at the county level across all specifications. *, **, and *** denotes significance level at 10%, 5%, and 1% respectively.

*The number of observations is smaller than 25,700 is because some municipalities have no population and GDP per capita data in some periods.

Table 5. Heterogeneous Impacts of Road Access on Population and GDP per Capita in Agricultural areas, Agricultural frontier, and Nonagricultural Areas: Difference-in-differences Combined with the Instrument Variables Approach.

	Agricultural areas		**Agricultural frontier**		**Nonagricultural areas**	
	OLS	IV	OLS	IV	OLS	IV
Dependent variable: logarithm of population						
Logarithm of distance to nearest road network	-0.217***	-0.401***	-0.203***	-0.349***	-0.131***	-0.250***
	(0.018)	(0.084)	(0.024)	(0.081)	(0.015)	(0.064)
*Logarithm of distance to nearest road network*Post trade reform*	-0.040***	-0.548***	-0.047**	-0.471***	-0.066***	-0.267***
	(0.014)	(0.110)	(0.019)	(0.089)	(0.010)	(0.040)
R-squared	0.403	0.122	0.385	0.186	0.497	0.438
First-stage F-statistics		26.626		29.788		73.226
Number of observations	9,939	9,939	5,011	5,011	8,396	8,396
Dependent variable: logarithm of GDP per capita						
Logarithm of distance to nearest road network	-0.089***	-0.411***	-0.106***	-0.304***	-0.123***	-0.219***
	(0.010)	(0.056)	(0.013)	(0.051)	(0.010)	(0.036)
*Logarithm of distance to nearest road network*Post trade reform*	0.025**	-0.060	0.028**	-0.041	0.061***	0.117***
	(0.010)	(0.057)	(0.014)	(0.050)	(0.009)	(0.028)
R-squared	0.499	0.186	0.512	0.401	0.642	0.635
State-by-year fixed effects	Y	Y	Y	Y	Y	Y
First-stage F-statistics		26.623		29.782		73.221
Number of observations	9,937	9,937	5,011	5,011	8,395	8,395

Notes: This table presents the OLS and IV estimation result of equation (2). We obtain the IV results by instrumenting distance to the nearest road with distance to the constructed road network. We include state-by-year fixed effects and cluster standard errors at the county level across all specifications. *, **, and *** denotes significance level at 10%, 5%, and 1% respectively.

Table 6. Impacts of Road Access, Trade Reform, and Export Intensity on Population and GDP per Capita: Triple Differences Combined with Instrument Variables Approach.

	Full		**Nonarid areas**		**Arid areas**		**Agricultural regions**		**Agricultural frontier**		**Nonagricultural areas**	
	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV
Dependent variable: logarithm of population												
Logarithm of distance to nearest road network	-0.178***	-0.347***	-0.209***	-0.359***	-0.107***	-0.562	-0.217***	-0.403***	-0.203***	-0.351***	-0.132***	-0.255***
	(0.012)	(0.053)	(0.014)	(0.053)	(0.020)	(0.438)	(0.018)	(0.085)	(0.024)	(0.080)	(0.015)	(0.064)
*Logarithm of distance to nearest road network*Post trade reform*	-0.062***	-0.315***	-0.050***	-0.293***	-0.037	1.774	-0.034	-0.524***	-0.064*	-0.585***	-0.088***	-0.210***
	(0.014)	(0.070)	(0.016)	(0.066)	(0.035)	(1.894)	(0.023)	(0.143)	(0.033)	(0.125)	(0.018)	(0.078)
*Logarithm of distance to nearest road network*Post trade reform*High export intensity*	0.019	-0.098	0.002	-0.174	0.005	-1.951	-0.010	-0.062	0.029	0.250	0.043	-0.116
	(0.023)	(0.131)	(0.027)	(0.128)	(0.044)	(2.227)	(0.035)	(0.250)	(0.046)	(0.196)	(0.030)	(0.151)
*High soybean production potential*Post trade reform*	-0.028	0.267	0.033	0.475	-0.064	4.956	0.111	0.186	-0.101	-0.736	-0.156**	0.248
	(0.059)	(0.320)	(0.070)	(0.310)	(0.118)	(5.682)	(0.092)	(0.625)	(0.132)	(0.544)	(0.075)	(0.364)
High soybean production potential	-0.009	-0.016	-0.014	-0.022	0.039	-0.022	0.005	-0.006	0.014	0.003	0.048	0.039
	(0.027)	(0.028)	(0.033)	(0.033)	(0.044)	(0.077)	(0.041)	(0.042)	(0.055)	(0.055)	(0.036)	(0.036)
Post trade reform	-1.011***	-0.289	-0.767***	-0.070	0.031	-4.973	-1.089***	0.992**	-0.952***	1.255***	-0.243	0.349
	(0.115)	(0.231)	(0.131)	(0.226)	(0.176)	(5.189)	(0.195)	(0.439)	(0.216)	(0.399)	(0.324)	(0.348)
R-squared	0.452	0.315	0.443	0.321	0.535	-0.237	0.404	0.114	0.385	0.196	0.497	0.432
First-stage F-statistics		36.980		44.011		0.525		10.365		12.800		27.721
Number of observations	23,463	23,463	17,917	17,917	5,512	5,512	10,729	10,729	5,860	5,860	12,700	12,700
Dependent variable: logarithm of GDP per capita												
Logarithm of distance to nearest road network	-0.109***	-0.313***	-0.108***	-0.265***	-0.085***	-0.759*	-0.089***	-0.410***	-0.107***	-0.298***	-0.123***	-0.214***
	(0.007)	(0.032)	(0.008)	(0.031)	(0.011)	(0.455)	(0.010)	(0.056)	(0.013)	(0.051)	(0.010)	(0.036)
*Logarithm of distance to nearest road network*Post trade reform*	0.044***	0.126***	0.038***	0.109***	0.059***	1.998	0.032**	0.052	0.038*	0.102	0.041***	0.093**

	(0.009)	(0.037)	(0.010)	(0.035)	(0.015)	(1.434)	(0.013)	(0.069)	(0.020)	(0.063)	(0.012)	(0.044)
*Logarithm of distance to nearest road network*Post trade reform*High export intensity*	0.006	-0.109*	0.006	-0.147**	-0.019	-1.654	-0.016	-0.237*	-0.017	-0.298***	0.036**	0.043
	(0.012)	(0.064)	(0.014)	(0.064)	(0.017)	(1.720)	(0.016)	(0.140)	(0.024)	(0.110)	(0.016)	(0.076)
*High soybean production potential*Post trade reform*	-0.023	0.254	-0.023	0.345**	0.040	4.282	-0.017	0.523	0.016	0.790***	-0.050	-0.070
	(0.032)	(0.158)	(0.038)	(0.156)	(0.045)	(4.375)	(0.045)	(0.347)	(0.073)	(0.300)	(0.044)	(0.186)
High soybean production potential	0.025	0.027	0.032	0.036*	0.009	-0.081	-0.012	-0.033	-0.053	-0.061*	0.022	0.025
	(0.016)	(0.018)	(0.020)	(0.021)	(0.026)	(0.078)	(0.023)	(0.028)	(0.033)	(0.035)	(0.023)	(0.023)
Post trade reform	1.119***	0.899***	0.972***	0.822***	0.946***	-4.506	1.291***	0.700***	1.234***	0.611***	1.138***	1.011***
	(0.068)	(0.121)	(0.082)	(0.121)	(0.104)	(3.921)	(0.096)	(0.221)	(0.111)	(0.206)	(0.111)	(0.163)
R-squared	0.644	0.585	0.506	0.452	0.595	-1.266	0.501	0.167	0.514	0.363	0.643	0.637
First-stage F-statistics		36.978		44.016		0.523		10.366		12.801		27.713
Number of observations	23,458	23,458	17,915	17,915	5,509	5,509	10,727	10,727	5,858	5,858	12,697	12,697

Notes: This table presents the estimation results of equation (3), in which we examine the interactive impacts of road access, trade reform, and export intensity on population and GDP per capita. We obtain the IV results by instrumenting distance to the nearest road with distance to the constructed road network. We include state-by-year fixed effects and cluster standard errors at the county level across all specifications. *, **, and *** denotes significance level at 10%, 5%, and 1% respectively.

Table 7. Impacts of Road Access, Trade Reform, and Export Intensity on Agricultural Outcomes: Triple Differences Combined with Instrument Variables Approach.

	Full		Nonarid areas		Arid areas		Agricultural regions		Agricultural frontier		Nonagricultural areas	
	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV
Dependent variable: logarithm of soybean harvested area												
Logarithm of distance to nearest road network	-0.329***	-1.227***	-0.432***	-1.339***	0.008	-0.174	-0.653***	-2.459***	-0.697***	-1.591***	-0.003	-0.076
	(0.032)	(0.153)	(0.041)	(0.162)	(0.006)	(0.154)	(0.060)	(0.339)	(0.070)	(0.239)	(0.016)	(0.064)
*Logarithm of distance to nearest road network*Post trade reform*	0.077	0.840***	0.092*	0.807***	0.015	0.744	0.148*	0.397	-0.128	-0.313	-0.050*	0.322***
	(0.048)	(0.204)	(0.056)	(0.206)	(0.019)	(0.938)	(0.084)	(0.491)	(0.122)	(0.377)	(0.029)	(0.120)
*Logarithm of distance to nearest road network*Post trade reform*High export intensity*	0.039	-1.503***	0.023	-1.450***	-0.054**	-0.473	0.097	-1.573	0.362**	-0.792	0.068*	-0.303
	(0.069)	(0.387)	(0.085)	(0.398)	(0.025)	(1.155)	(0.118)	(0.972)	(0.161)	(0.692)	(0.041)	(0.193)
*High soybean production potential*Post trade reform*	-0.197	3.551***	-0.195	3.352***	0.125	1.220	-0.713**	3.428	-1.314***	1.828	-0.021	0.839*
	(0.174)	(0.948)	(0.215)	(0.965)	(0.077)	(2.925)	(0.313)	(2.422)	(0.454)	(1.902)	(0.107)	(0.465)
High soybean production potential	0.163**	0.178**	0.166*	0.190*	0.026**	0.008	-0.066	-0.222	-0.041	-0.058	0.176***	0.184***
	(0.075)	(0.079)	(0.096)	(0.100)	(0.011)	(0.019)	(0.138)	(0.162)	(0.156)	(0.162)	(0.032)	(0.032)
Post trade reform	2.920***	0.795	1.883***	0.118	-0.044	-2.112	5.625***	1.039	5.606***	3.588***	2.378	1.344
	(0.402)	(0.706)	(0.440)	(0.741)	(0.059)	(2.552)	(0.542)	(1.539)	(0.619)	(1.206)	(1.588)	(1.574)
R-squared	0.474	0.383	0.446	0.374	0.227	0.035	0.367	0.073	0.378	0.228	0.291	0.277
First-stage F-statistics		37.715		44.846		0.517		10.688		12.883		28.024
Number of observations	25,700	25,700	19,695	19,695	5,965	5,965	12,070	12,070	6,480	6,480	13,590	13,590
Dependent variable: logarithm of soybean yield												
Logarithm of distance to nearest road network	-0.252***	-1.178***	-0.328***	-1.294***	0.009	-0.196	-0.506***	-2.356***	-0.593***	-1.381***	-0.009	-0.041
	(0.029)	(0.145)	(0.038)	(0.155)	(0.009)	(0.180)	(0.055)	(0.320)	(0.065)	(0.221)	(0.021)	(0.080)

*Logarithm of distance to nearest road network*Post trade reform*	0.103**	0.819***	0.117**	0.788***	0.013	1.280	0.177**	0.254	-0.094	-0.284	-0.053	0.396***
	(0.047)	(0.202)	(0.055)	(0.204)	(0.024)	(1.750)	(0.081)	(0.491)	(0.114)	(0.364)	(0.037)	(0.150)
*Logarithm of distance to nearest road network*Post trade reform*High export intensity*	-0.014	-1.350***	-0.032	-1.255***	-0.056*	-1.204	0.010	-1.173	0.268*	-0.630	0.078	-0.288
	(0.063)	(0.364)	(0.079)	(0.374)	(0.029)	(2.102)	(0.107)	(0.906)	(0.143)	(0.620)	(0.050)	(0.229)
*High soybean production potential*Post trade reform*	-0.140	3.099***	-0.157	2.777***	0.107	3.055	-0.667**	2.254	-1.216***	1.223	-0.010	0.831
	(0.167)	(0.896)	(0.208)	(0.913)	(0.088)	(5.336)	(0.296)	(2.267)	(0.423)	(1.719)	(0.132)	(0.555)
High soybean production potential	0.318***	0.335***	0.377***	0.404***	0.039**	0.019	0.096	-0.067	-0.007	-0.022	0.233***	0.244***
	(0.071)	(0.075)	(0.091)	(0.096)	(0.018)	(0.025)	(0.127)	(0.154)	(0.153)	(0.157)	(0.040)	(0.039)
Post trade reform	2.935***	0.941	2.166***	0.540	-0.034	-3.549	5.025***	1.205	5.058***	3.343***	2.187	0.859
	(0.372)	(0.686)	(0.404)	(0.714)	(0.070)	(4.752)	(0.485)	(1.546)	(0.565)	(1.188)	(1.496)	(1.510)
R-squared	0.442	0.355	0.394	0.322	0.201	-0.317	0.298	-0.030	0.315	0.194	0.268	0.253
First-stage F-statistics		37.715		44.846		0.517		10.688		12.883		28.024
Number of observations	25,700	25,700	19,695	19,695	5,965	5,965	12,070	12,070	6,480	6,480	13,590	13,590

Notes: This table presents the estimation results of equation (3), in which we examine the interactive impacts of road access, trade reform, and export intensity on soybeans harvested acreage, soybean yield, and total agricultural production value. We obtain the IV results by instrumenting distance to the nearest road with distance to the constructed road network. We include state-by-year fixed effects and cluster standard errors at the county level across all specifications. *, **, and *** denotes significance level at 10%, 5%, and 1% respectively.

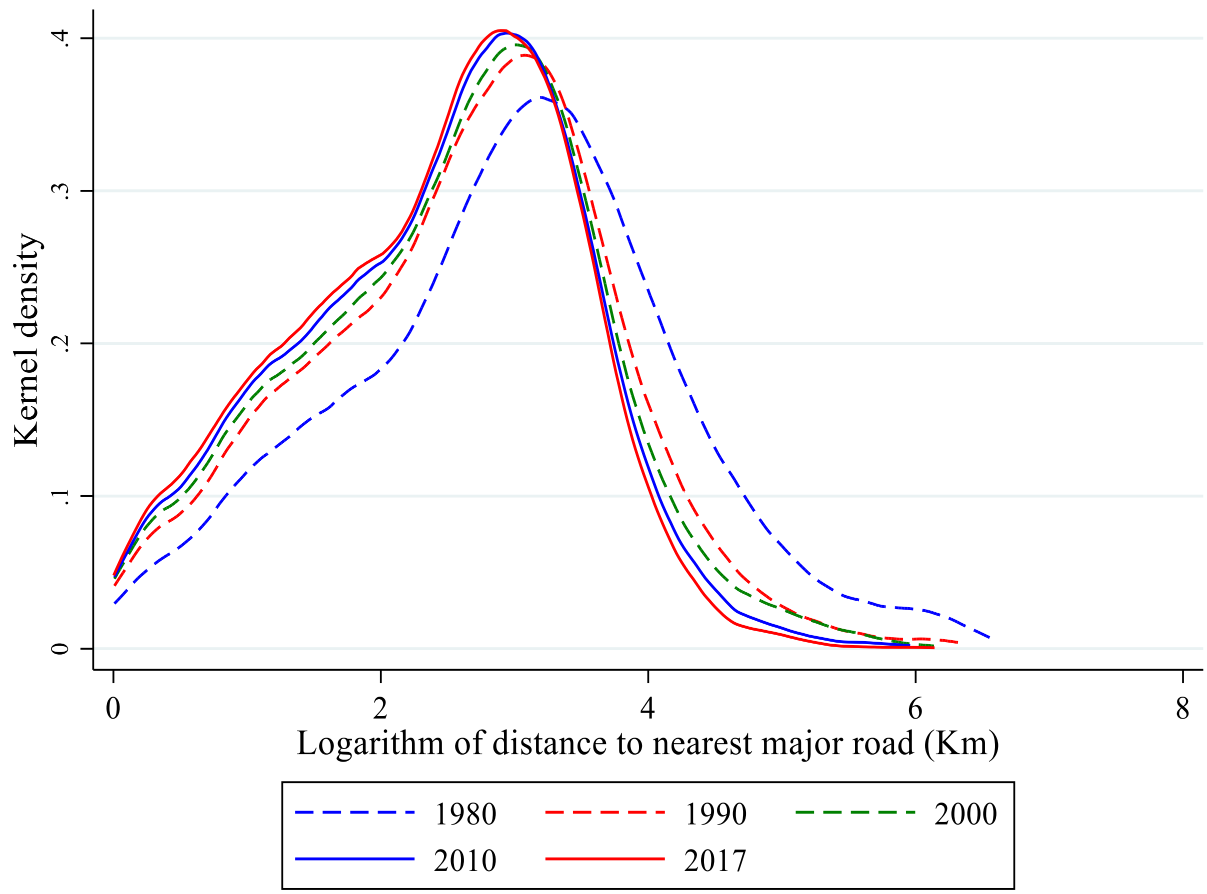
Appendix

"Roads, Trade, and Development: Evidence from the Agricultural Boom in Brazil"

Figure A1. Brazil's Six Biomes and Five Regions.

Notes: This map shows Brazil's six biomes (Amazônia, Cerrado, Caatinga, Mata Atlântica, Pantanal and Pampa) with five regions (North, Northeast, Central-west, Southeast, and South). The biomes map results from a partnership between the Brazilian Ministry of Environment (MMA) and the Brazilian Institute of Geography and Statistics (IBGE). See https://data.globalforestwatch.org/datasets/54ec099791644be4b273d9d8a853d452_4?geometry=-121.155%2C-29.328%2C12.351%2C0.062 for a detailed description of the vegetation within each biome.

Figure A2. Distribution of municipality's distance to nearest major road network over time.



Notes: This figure presents the distribution of the logarithm of distance from a municipality's centroid to its nearest major road network in 1980, 1990, 2000, 2010, and 2017.

Table A1. Impacts of Road Access, Trade Reform, and Export Intensity on Corn Planted Acreage and Yield: Triple Differences Combined with Instrument Variables Approach.

	Full		Nonarid areas		Arid areas		Agricultural regions		Agricultural frontier		Nonagricultural areas	
	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV
Dependent variable: logarithm of soybean harvested area												
Logarithm of distance to nearest road network	-0.242***	-0.439***	-0.298***	-0.545***	0.001	0.038	-0.401***	-1.136***	-0.486***	-0.854***	-0.086*	0.280
	(0.039)	(0.158)	(0.044)	(0.156)	(0.079)	(1.554)	(0.058)	(0.273)	(0.068)	(0.210)	(0.052)	(0.192)
*Logarithm of distance to nearest road network*Post trade reform*	0.211***	0.748***	0.241***	0.510***	-0.048	-2.290	0.263***	0.147	0.175**	0.263	0.116*	0.854***
	(0.045)	(0.173)	(0.050)	(0.169)	(0.101)	(4.391)	(0.067)	(0.338)	(0.086)	(0.241)	(0.061)	(0.222)
*Logarithm of distance to nearest road network*Post trade reform*High export intensity*	-0.012	-0.189	-0.036	-0.482*	0.057	6.216	0.045	0.725	0.154*	0.599**	-0.009	-0.236
	(0.050)	(0.261)	(0.057)	(0.260)	(0.096)	(5.451)	(0.071)	(0.479)	(0.083)	(0.301)	(0.070)	(0.337)
*High soybean production potential*Post trade reform*	0.084	0.495	0.159	1.229*	-0.157	-15.676	-0.329	-2.018*	-0.017	-1.256	0.199	0.671
	(0.150)	(0.645)	(0.172)	(0.640)	(0.292)	(13.908)	(0.224)	(1.209)	(0.283)	(0.846)	(0.202)	(0.815)
High soybean production potential	-0.065	-0.052	-0.052	-0.044	0.010	0.019	-0.235*	-0.306**	-0.537***	-0.542***	0.026	0.041
	(0.093)	(0.093)	(0.105)	(0.105)	(0.199)	(0.240)	(0.138)	(0.144)	(0.165)	(0.166)	(0.128)	(0.130)
Post trade reform	-0.273	-1.790***	-1.423***	-2.105***	4.680***	10.254	0.203	0.693	-0.245	0.383	-0.126	-2.789***
	(0.359)	(0.576)	(0.335)	(0.545)	(0.726)	(12.144)	(0.682)	(1.126)	(0.727)	(0.859)	(0.755)	(0.854)
R-squared	0.255	0.248	0.290	0.281	0.234	-0.659	0.232	0.180	0.294	0.281	0.239	0.163
First-stage F-statistics		37.715		44.846		0.517		10.688		12.883		28.024
Number of observations	25,700	25,700	19,695	19,695	5,965	5,965	12,070	12,070	6,480	6,480	13,590	13,590
Dependent variable: logarithm of soybean yield												

Logarithm of distance to nearest road network	-0.235***	-0.477***	-0.279***	-0.385**	0.018	-1.608	-0.329***	-0.742***	-0.372***	-0.652***	-0.150***	-0.159
	(0.036)	(0.149)	(0.043)	(0.151)	(0.059)	(1.456)	(0.055)	(0.251)	(0.066)	(0.203)	(0.047)	(0.182)
*Logarithm of distance to nearest road network*Post trade reform*	0.233***	0.725***	0.261***	0.449**	-0.016	2.540	0.262***	0.170	0.219***	0.729***	0.183***	0.936***
	(0.044)	(0.178)	(0.051)	(0.179)	(0.078)	(2.511)	(0.066)	(0.324)	(0.079)	(0.230)	(0.060)	(0.228)
*Logarithm of distance to nearest road network*Post trade reform*High export intensity*	0.009	0.156	-0.003	-0.079	0.018	1.035	0.061	0.744*	0.135**	0.232	-0.015	0.015
	(0.046)	(0.243)	(0.053)	(0.239)	(0.078)	(2.705)	(0.064)	(0.417)	(0.066)	(0.246)	(0.066)	(0.318)
*High soybean production potential*Post trade reform*	-0.089	-0.477	-0.044	0.128	-0.114	-2.460	-0.535**	-2.229**	-0.056	-0.310	0.181	0.018
	(0.144)	(0.604)	(0.170)	(0.592)	(0.240)	(6.899)	(0.211)	(1.054)	(0.239)	(0.705)	(0.200)	(0.778)
High soybean production potential	0.080	0.097	0.097	0.104	0.079	-0.075	0.030	-0.011	-0.418***	-0.421***	0.072	0.107
	(0.085)	(0.085)	(0.102)	(0.102)	(0.147)	(0.229)	(0.130)	(0.132)	(0.156)	(0.156)	(0.114)	(0.113)
Post trade reform	2.429***	1.033*	0.338	-0.152	5.561***	-2.169	2.342***	3.136***	1.842***	1.320	2.644***	0.014
	(0.344)	(0.587)	(0.279)	(0.536)	(0.610)	(7.112)	(0.643)	(1.111)	(0.677)	(0.856)	(0.397)	(0.708)
R-squared	0.378	0.368	0.372	0.372	0.321	-0.131	0.378	0.360	0.495	0.485	0.343	0.306
First-stage F-statistics		37.715		44.846		0.517		10.688		12.883		28.024
Number of observations	25,700	19,695	19,695	5,965	5,965	12,070	12,070	6,480	6,480	13,590	13,590	13,590

Note: This table presents the estimation results of equation (3), in which we examine the interactive impacts of road access, trade reform, and export intensity on corn harvested acreage, corn yield. We obtain the IV results by instrumenting distance to the nearest road with distance to the constructed road network. We include state-by-year fixed effects and cluster standard errors at the county level across all specifications. *, **, and *** denotes significance level at 10%, 5%, and 1% respectively.