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Responsiveness of market equilibrium agricultural output, price and land use to shocks

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Abstract

We assess the responsiveness of market equilibrium agricultural output, price and land use to shocks in agricultural demand, land yield and arable land area and the role of road infrastructure policy in offsetting them. We adapt a partial equilibrium model in the agricultural composite good and lands markets to guide the specification and estimation of a simultaneous equation model (SEM) for agricultural demand, land yield and acreage, and calculate market equilibrium responsiveness. We estimate the SEM by the generalised method of moments three-stage least squares (GMM 3SLS) using a panel data set of the 10 biggest agricultural producer states in Brazil from 2001 to 2017. Using demand, land yield and acreage price elasticity estimates, we find that Brazil may expand equilibrium agricultural output while preserving its native vegetation land and dampening long-term agricultural price escalation under a scenario of increasing worldwide demand for food, fibre and fuel and adverse climate shocks. Using acreage and land yield freight rate elasticity estimates, we show how shocks may be offset by road infrastructure policies that reduce freight rates to specific destination states, as they may be designed to induce less equilibrium land use for the same equilibrium output or raise equilibrium output with less equilibrium land use.

KEYWORDS

agricultural output, elasticities, generalised method of moments, land use and yield, simultaneous equation models

JEL CLASSIFICATION

Q11, Q15, Q18, O18, C33

1 | INTRODUCTION

The global demand for food, fibre and fuel is expected to grow significantly by 2050 because of population growth and increased urbanisation. Thus, it is of increasing interest to examine how agricultural prices and output will respond to the growth in demand for food, fibre and fuel and to adverse climate shocks that may affect yields and arable land area for two main reasons. Firstly, the rise in agricultural prices may have a devastating impact on the world's poor. Secondly, agricultural output expansion may exert considerable pressure on the world's natural resource base (Hertel, 2011), exacerbating existing concerns of the need to preserve native vegetation to maintain the current provision of public services and goods (e.g. the maintenance of viable species' gene pools, nutrient cycling, water filtering and soil and water conservation).

The first aim of this study was to assess the responsiveness of the market equilibrium agricultural output, price and land use to shocks in the demand for food, fibre, fuel, and shocks to crop yields and arable land area in Brazil, a major agricultural producer that also preserves 66.3% of its land under native vegetation (Calil & Ribera, 2019; Embrapa, 2020).

We adapt a partial equilibrium model in the agricultural composite good and lands markets, which we connect to the closed forms proposed by Hertel (2011). We estimate the intensive and extensive margin price elasticities of agricultural supply and the price elasticity of agricultural demand in a simultaneous equation model (SEM). Furthermore, as Brazil ranks 112th among 140 countries in terms of quality of road infrastructure (WEF, 2019), we investigate how road infrastructure policies could be designed to neutralise shocks in the demand for food, fibre, fuel, land yield and arable land area. Accordingly, we use freight rate elasticities of agricultural acreage, land yield and supply from the estimation of an SEM.

Brazil is an ideal country to study as it is one of the largest agricultural exporters worldwide (Calil & Ribera, 2019; USITC, 2012). In addition, it uses only 30.2% of its land for agriculture, livestock and forestry (Embrapa, 2020). The farm sector contributes 6.6% in Brazilian Gross Domestic Product and employs 9.4% of its formal labour force (CIA, 2022). Brazil is a prominent member of a 13-country group that manages 60% of the world's 1.4 million hectares of arable land that has not been converted to agriculture, livestock, forestry, protected areas or urbanised areas (Alexandratos & Bruinsma, 2012).

Our study makes three contributions to the existing literature. The first is that we jointly estimate the price elasticity of demand, and intensive and extensive margin price elasticities of supply of the agricultural composite good. Consequently, our study makes it feasible to estimate and test hypotheses on the responsiveness of the market equilibrium for agricultural output, price and land use to shocks in Brazil. Unlike our study, prior works have separately estimated price elasticities of demand (Coelho et al., 2010; Menezes et al., 2008; Muhammad et al., 2013; Pintos-Payeras, 2009) and supply (Castro & Teixeira, 2012; Hausman, 2012; Iqbal & Babcock, 2018; Menezes & Piketty, 2012). Furthermore, these studies have considered either groups of agricultural products or specific crops (e.g. soybean, sugarcane, cotton, wheat, corn and rice) rather than focussing on the agricultural composite good. Presently, only Barr et al. (2011) focussed on the agricultural composite good, calculating the extensive margin price elasticity of supply but assume the intensive margin price elasticity of supply to be insignificant (Keeney & Hertel, 2008). Moreover, Barr et al. (2011) utilised a simple algebraic calculation in contrast to the econometric approach pursued in our study that allows for statistical inference.

Second, this study overcomes inconsistent estimation due to omitted variables (e.g. freight rates) and ignored agricultural price endogeneity as price is simultaneously determined by supply and demand. The SEM used in this study includes freight rates and is estimated by the generalised method of moments three-stage least squares (GMM 3SLS) to overcome the omission of variable bias and price endogeneity. The SEM also includes state and time fixed effects (i.e. a two-way error component or two-way fixed effects) following Brückner (2013), Kim and Pyun (2018) and Baltagi (2021), state-specific time trends to control for the potential unobservable confounding factors and uses robust standard errors to cluster correlation at the state level to fix statistical inference.

Third, this study explores the effects of rising prices and freight rates on yields and land use at the market level, holding the other variables fixed, with a two-component land use model grounded on locational land rent maximisation, based on von Thünen's (1826) and Ricardo's (1817) theories. Therefore, our conceptual and econometric framework could guide similar studies for other countries and regions.

The remainder of this study is organised as follows: Section 2 explores the effects of an increase in prices and freight rates on yields and acreage at the market level; Section 3 presents the specification of our SEM for agricultural demand, yield and acreage and describes the panel data used in the study; Section 4 discusses the estimation procedures and results; Section 5 provides policy implications; and Section 6 concludes the study.

2 | CONCEPTUAL FRAMEWORK

The theoretical grounding is used to analyse the effects of an increase in prices and freight rates on agricultural land yield and acreage at the market level, holding all other variables fixed. We first present a 2-component land use model based on Beckmann (1972), Heijman and Schipper (2010), Fujita and Thisse (2013) and Miao et al. (2016). The locational land rent maximisation model is the first component from which we obtain the effects of an increase in prices and freight rates on agricultural output per land unit, i.e. the intensive margin effects. The model of land allocation to activities around an isolated marketplace is the second component from which we obtain the effects of an increase in prices and freight rates on agricultural acreage, i.e. the extensive margin effects. Next, we combine the intensive and extensive margin effects to examine the effects of an increase in prices and freight rates on agricultural acreage and land yield at the market level. Lastly, we make the connection between the partial equilibrium model in the agricultural composite good and land markets to Hertel's (2011) closed forms for the responsiveness of market equilibrium output, price and land use to shocks. All these guide the specification, selection, estimation and result interpretation of the econometric models.

2.1 | Locational land rent maximisation model

Following von Thünen (1826), we consider an isolated marketplace surrounded by land area units $l = 1, 2, \ldots, L$ characterised by vectors (d, c, τ), where d is the distance to the marketplace, c is the soil quality (i.e. type, fertility and physical properties of soil and climate) and τ is the land unit fixed effects (i.e. topography and geographical location). Each land area unit is allocated to an activity $j = 1, 2, \ldots, J$ (e.g. agriculture, livestock, forestry and fallow) that, under constant returns to scale (Beckmann, 1972), produces a composite output j according to the function $q_j(I_j, c, \tau) \geq 0$, using $I_j \geq 0$ units of composite input j.

We refer to composites output and input of activity j simply as output and input j, and omit reference to c and τ, writing $q_j(I_j)$. At a given output price p_j, freight rate f_j and input price w_j, agents maximise, with respect to I_j,

$$P_j q_j(I_j) - \mathrm{w}_j I_j, \tag{1}$$

where $P_j := \mathrm{p}_j - f_j d$ is the net price of output j.

We restrict attention to configurations of non-negative parameters p_j,f_j and d, for which $P_j > 0$, as it makes activity j viable in the absence of 'free-lunch' (i.e. $q_j(0) = 0$), and assume that the maximisation of Equation (1) produces a unique interior solution I_j^* that satisfies the first-order condition, $P_j q_j'\left(I_j^*\right) - w_j = 0$ (see Lau (1978) for general sufficient conditions for a unique interior solution in a profit maximisation setting). Thus, for activity j, the land use intensity function is $I_j^* = I_j(p_j, w_j, f_j, d, c, \tau)$, the output function is $q_j^* = q_j\left(I_j^*, c, \tau\right)$ and the locational land rent function is $R_j^* = P_j q_j^* \text{-} w_j I_j^*$.

We use the following assumptions: $q_j'\left(I_j\right) < 0, q_j''\left(I_j\right) < 0, \frac{\partial q_j}{\partial c} > 0, \frac{\partial I_j^*}{\partial c} > 0$ (i.e. Ricardo's (1817) assumption by which land use intensity increases in land quality), and the first-order condition $P_j q_j'\left(I_j^*\right) - w_j = 0$. We apply the implicit function theorem (details given in the Appendix S1) to obtain the following three results.

Result 1. The land output j increases in own price.

Result 2. The land output j decreases in this activity's input price, freight rate, transportation cost and distance to the marketplace.

Result 3. As land output and rent both increase in land quality, a new land unit entering an activity is necessarily of lower quality. Thereby, the activity j's land yield (i.e. the average land output of activity j) decreases if a land unit enters activity j.

2.2 | Model of the circular land area allocated to agriculture around an isolated marketplace

We first examine the effects of an increase in prices and freight rates on the radius of the circular land area around an isolated marketplace that has been allocated to the agriculture activity $j = 1$. As the circular area has been allocated to agriculture, $R_1^* - R_2^* \geq 0$ (i.e. the locational land rent of each land unit in this circular area is greater than if it had been allocated to Activity 2 (e.g. livestock)) and $R_2^* \geq R_j^*, j \geq 3$, that is the locational land rent of each land unit, had it been allocated to Activity 2, would be greater than if it had been allocated to any other activity, except for agriculture. Moreover, as a locational land rent function decreases in distance (i.e. $\frac{\partial R_j^*}{\partial d} = -f_j q_j^* < 0$) at increasing rates (i.e. $\frac{\partial^2 R_j^*}{\partial d^2} = -f_j q_j'\left(I_j^*\right)\frac{\partial I_j^*}{\partial d} > 0$), the circular land area allocated to agriculture is of maximum radius $d_{max} = p_1 / f_1$ if $R_2^* \leq 0$ at d_{max}; otherwise, if $R_2^* \geq 0$ at d_{max}, the circular land area allocated to agriculture is of radius d^* lower than d_{max}, at which $R_1^* - R_2^* = 0$ and $f_1 q_1^* - f_2 q_2^* > 0$, that is R_1^* is steeper than R_2^*. Hence, we derive the following 3 Results (see the Appendix S1 for full derivation).

Result 4. The effects of an increase in the prices of the agricultural output and input on the land area allocated to agriculture are positive and nonpositive, respectively.

Result 5. The effects of an increase in the prices of livestock output and input on the land area allocated to agriculture are nonpositive and non-negative, respectively.

Result 6. The effects of an increase in the freight rate of agriculture and livestock (i.e. a competing activity for land with agriculture) on the land area allocated to agriculture are negative and non-negative, respectively.

2.3 | Effects of an increase in prices and freight rates on agricultural acreage and land yield at the market level

Based on Results 1–3 for agricultural land yield and Results 4–6 for agricultural acreage, we examine the net effects of a rise in prices and freight rates on agricultural acreage and land yield (i.e. the average land output for agriculture).

The net effects on agricultural acreage depend on how the area occupied by agriculture shrinks or expands according to Results 4–6 (i.e. the direct acreage effect) and whether land units within this area become profitable and enter agriculture or become unprofitable and leave agriculture (i.e. the indirect acreage effect). For example, the net effect at the market level of an agricultural price rise on agricultural acreage is positive as, in response, more distant land units switch from livestock to agriculture based on Result 4 (i.e. the direct acreage effect), and unused land units in the area already occupied by agriculture may become profitable (i.e. the indirect acreage effect) and enter agriculture. The net effects on agricultural acreage are summarised in Table 1.

In turn, the net effects on agricultural land yield depend on how agriculture land use intensity responds as given by Results 1–3. For example, the net effect of an agricultural price rise on yield is ambiguous as it induces a more intensive use of land units already used for agriculture (Result 1), which increases yield. However, land units that may become profitable and enter agriculture in the area already occupied by agriculture are necessarily of lower quality (Result 3), which decreases yield. Moreover, more distant land units that switch to agriculture use are of unknown quality. The net effects on agricultural yields are summarised in Table 2.

2.4 | Partial equilibrium model in the agricultural composite good and lands markets

This section presents the partial equilibrium model in the agricultural composite good and lands markets, connecting it to Hertel's (2011) closed forms for the responsiveness of market equilibrium output, price and land use to shocks.

Given activities $j = 1, 2, \ldots, J$, land area units $l = 1, 2, \ldots, L$ characterised by vectors (d, c, τ), functions $q_j(I_j, c, \tau) \geq 0$, freight rates f_j, input prices w_j, agricultural price $ownprice = p_1$, and the prices of other activities p_j for $j > 1$, per capita income $gnppc$, the demand function of the agricultural (composite) good $demand = demand(ownprice, p_2, \ldots, p_J, gnppc)$ and the interest rate r, a competitive equilibrium is composed of:

a. Sets of land use intensities $\mathbf{I}_l^*$ that maximise Equation (1) for the activity of the highest locational land rent, and implied sets of land outputs q_l^*, land rents R_l^* and land prices $lp_l := R_l^*/r$, that is the zero profit or free entry condition;
b. Subsets $L(j)$ of land units allocated to activity j, such that, as $j = 1$ denotes agriculture, the agricultural supply function is $supply = \sum_{l \in L(j=1)} q_l^*$, that is the sum of land outputs in the subset of lands allocated to agriculture $L(j = 1)$; and
c. An agricultural price $ownprice^*$ that equals $supply(.)$ to $demand(.)$, such that the agricultural composite good and lands markets clear.

We connect the partial equilibrium model equilibrium to Hertel's (2011) closed forms taking the following 6 steps.

First, as the agricultural supply is the yield per hectare (i.e. the average land output for agriculture) times acreage (i.e. the sum of land units in subset $L(j = 1)$), the (instantanous) percentage change in agricultural supply is

$$\Delta\,\%\,supply = \Delta\,\%\,yield + \Delta\,\%\,acreage, \tag{2}$$

where $\Delta\,\%\,yield$ and $\Delta\,\%\,acreage$ are the percentage change in yield and in acreage, repectively.

Second, following Hertel (2011), we set

$$\Delta\,\%\,yield = \beta_{22}\,\Delta\,\%\,ownprice + \Delta_L^D \tag{3}$$

TABLE 1 Effects of increases in parameters of agriculture and livestock locational land rent functions on agricultural acreage.

Increase in the parameter, holding all other variables constant	Direct effect (i.e. caused by the response in the area allocated to agriculture)	Indirect effect (i.e. caused by the entry or exit of land units from agriculture)	Net effect at the market level
Agricultural price, p_1	Positive (By Result 4)	Non-negative (From Expression [1])	Positive
Agricultural input price, w_1	Nonpositive (By Result 4)	Nonpositive (From Expression [1])	Nonpositive
Livestock output price, p_2	Nonpositive (By Result 5)	Null (From Expression [1])	Nonpositive
Livestock Input price, w_2	Non-negative (By Result 5)	Null (From Expression [1])	Non-negative
Agricultural freight rate, f_1	Negative (By Result 6)	Nonpositive (From Expression [1])	Negative
Livestock freight rate, f_2	Non-negative (By Result 6)	Null (From Expression [1])	Non-negative

TABLE 2 Effects of increases in parameters of the agriculture and livestock locational land rent functions on agricultural land yield.

Increase in the parameter, holding all other variables constant	Intensive margin effect (i.e. caused by the response in agricultural land use intensity)	Extensive margin effect (i.e. caused by the change in agricultural acreage)	Net effect at the market level
Agricultural price, p_1	Positive (By Result 1)	Ambiguous	Ambiguous
Agricultural input price, w_1	Negative (By Result 2)	Ambiguous, if acreage decreases in w_1; null, if acreage does not respond to w_1	Ambiguous, if acreage decreases in w_1; negative, if acreage does not respond to w_1
Livestock output price, p_2	Null (From Expression [1])	Ambiguous, if acreage decreases in p_2; null, if acreage does not respond to p_2	Ambiguous, if acreage decreases in p_2; null, if acreage does not respond to p_2
Livestock input price, w_2	Null (From Expression [1])	Ambiguous, if acreage increases in w_2; null, if acreage does not respond to w_2	Ambiguous, if acreage increases in w_2; null, if acreage does not respond to w_2
Agricultural freight rate, f_1	Negative (By Result 2)	Ambiguous	Ambiguous
Livestock freight rate, f_2	Null (From Expression [1])	Ambiguous, if acreage increases in f_2; null, if acreage does not respond to f_2	Ambiguous, if acreage increases in f_2; null, if acreage does not respond to f_2

$$\Delta\,\%\,acreage = \beta_{23}\,\Delta\,\%\,ownprice - \Delta_L^S \quad (4)$$

where β_{22} is the agricultural land yield price elasticity or the intensive margin elasticity, β_{23} is the agricultural acreage price elasticity or the extensive margin price elasticity, $\Delta\,\%\,ownprice$ is the agricultural price percentage change, Δ_L^D is the exogenous percentage growth in agricultural land yield (e.g. from changes in freight rates, prices prices of other activities' outputs and inputs, and benefitial climate shocks) and Δ_L^S is the exogenous percentage decay in arable land (e.g. from changes in freight rates, prices of other activities' outputs and inputs, derimental climate shocks, new legal restrictions and conversion of land to urban sprawn).

Third, we set the percentage change in agricultural demand as

$$\Delta\,\%demand = \beta_{21}\,\Delta\,\%ownprice + \Delta_A^D, \tag{5}$$

where β_{21} is the agricultural demand price elasticity, and Δ_A^D is the percentage growth in agricultural demand (e.g. from growths in population, urbanisation and per capita income, changes in prices of other goods such as meat and government-imposed biofuel mandates).

Fourth, setting $\Delta\,\%demand = \Delta\,\%supply$, we obtain that the percentage change in the market equilibrium agricultural price in response to shocks is

$$\Delta\,\%ownprice^{*} = \frac{\Delta_A^D - \Delta_L^D + \Delta_L^S}{|\beta_{21}| + \beta_{22} + \beta_{23}}, \tag{6}$$

such that the less than 1 is the inverse of the denominator (i.e. the inverse of the sum of the absolute value of agricultural demand, land yield and acreage price elasticities), the greater is the capacity of the economy to absorb the pressure for agricultural price rises arising from shocks.

Fifth, plugging Equation (6) into (4), replacing $\Delta\,\%ownprice$ with $\Delta\,\%ownprice^{*}$ and $\Delta\,\%acreage$ with $\Delta\%supply_L^{*}$, we obtain that the percentage change in the market equilibrium agricultural land use in response to shocks is:

$$\Delta\,\%supply_L^{*} = \frac{\Delta_A^D - \Delta_L^D + \Delta_L^S}{1 + \frac{|\beta_{21}|}{\beta_{32}} + \frac{\beta_{22}}{\beta_{32}}} - \Delta_L^S. \tag{7}$$

Thereby, the larger the (absolute) demand and land yield price elasticities are relative to the acreage price elasticity, the greater the capacity of the economy to absorb the pressure for agricultural land use expansion arising from shocks.

Finally, we obtain the percentage change in the market equilibrium agricultural output in response to exogenous shocks by plugging Equation (6) into (2), replacing $\%ownprice$ with $\Delta\,\%ownprice^{*}$.

3 | ECONOMETRIC MODEL AND DATA

This section presents our econometric model based on the partial equilibrium model in the agricultural composite good and lands markets, such that agricultural yield and acreage depend on agricultural price, agricultural input price, prices of other activities' outputs and inputs, freight rates, distances of land units to the marketplace, soil quality, topography and geographical location. We focus on livestock as the only activity that may compete with agriculture for land, because most new cropland in Brazil was previously pasture (Ferreira Filho et al., 2015). Thus, we specify the agricultural demand function as structural Equation (8), the agricultural land yield function as behavioural Equation (9) and the agricultural acreage function as structural Equation (10). These three equations pass the order and rank conditions for identification as we prove in the Appendix S1, such that our SEM is:

$$\begin{aligned} ldemand_{st} = {} & \beta_{11} + \beta_{21}\,lownprice_{st} + \beta_{31}\,lfedcattle_{st} + \beta_{41}\,lipca_{st} + \\ & \beta_{51}\,lgnppc_{st} + \alpha_{s1}\,trend + \nu_{s1} + \theta_{t1} + u_{st1} \end{aligned} \tag{8}$$

$$lyield_{st} = \beta_{12} + \beta_{22} lownprice_{st} + \beta_{32} lppi_{st} + \beta_{42} lfedcattle_{st} + \beta_{52} lsteer_{st} + \beta_{62} ldiesel_{st} + \sum_{i=1}^{27} \beta_{(i+6)2} lfr_{ist} + \alpha_{s2} trend + \nu_{s2} + \theta_{t2} + u_{st2} \quad (9)$$

$$lacreage_{st} = \beta_{13} + \beta_{23} lownprice_{st} + \beta_{33} lppi_{st} + \beta_{43} lfedcattle_{st} + \beta_{53} lsteer_{st} + \beta_{63} ldiesel_{st} + \sum_{i=1}^{27} \beta_{(i+6)3} lfr_{ist} + \alpha_{s3} trend + \nu_{s3} + \theta_{t3} + u_{st3} \quad (10)$$

where all the variables with an initial *l* are log-transformed, βs and αs are parameters, ν_{sg} is state fixed effects, θ_{tg} is year fixed effects, u_{stg} is a random error term, subscript 's' denotes state = 1, …, 10 (i.e. São Paulo, Paraná, Rio Grande do Sul, Minas Gerais, Mato Grosso, Bahia, Goiás, Santa Catarina, Mato Grosso do Sul and Espírito Santo), subscript 't' denotes year = 2001, …, 2017 and subscript 'g' denotes the first, second and third structural equation of the SEM.

The 10 biggest agricultural producer states in Brazil mentioned above are also the largest consumers, and so they represent the market in our model. However, as state consumer preferences may be influenced by factors that are fixed over time, affected by year-specific common shocks to all states and by unobserved factors following a time trend, we include state and time fixed effects and time trends in the demand Equation (8) to control for those factors. As distance to the marketplace, soil quality, topography and geographical location all affect agricultural yield and acreage according to our model, we include state and year fixed effects and time trends by state in the yield (9) and acreage (10) equations to control for these factors. Furthermore, those components may control for common price shocks or technological breakthroughs, as their common effect across states cannot be distinguished from year fixed effects, and their time-variant effects cannot be distinguished from the effect of the time trend variable.

Table 3 provides the list of variables with descriptions and data sources.

Using a balanced panel data set with 10 states and 17 years, each variable has 170 observations, and their descriptive statistics are given in Table 4.

4 | ESTIMATION PROCEDURES AND RESULTS

This section discusses the procedures used in the estimation of the SEM and estimation results.

From the partial equilibrium model in the agricultural composite good and lands markets, except for *lownprice*, all other 68 variables on the right-hand side of equations in the SEM are exogenous.[1] These variables enter each equation of the SEM either as an included instrument (i.e. a variable that is both explanatory and instrumental) or an excluded instrument (i.e. a variable that is only instrumental). Thereby, in Equations (9) and (10), *lipca* and *lgnppc* are excluded instruments as they enter equations only as instruments of *lownprice*, while the other 66 exogenous variables are included instruments as they enter equations as both explanatory variables and instruments of *lownprice*. In Equation (8), the variables *lppir*, *lsteer*, *ldiesel* and the 27 freight rates are excluded instruments, while the other 38 exogenous variables are included instruments. This means that Equations (9) and (10) end up with 104 degrees of freedom each and Equation (8) with 132 degrees of freedom, which carries no problem in terms of lack of degrees of freedom for the SEM estimation.

The excluded instruments (i.e. *lipca* and *lgnppc*) in Equations (9) and (10) satisfy the exclusion restriction for an instrumental variable (Angrist & Pischke, 2009; Pearl, 2009) as, conditionally

[1]The 1 × 68 exogenous vector in every equation is $\mathbf{w}_{st}$:= (*one*, $lfedcattle_{st}$, $lipca_{st}$, $lgnppc_{st}$, $lppi_{st}$, $lsteer_{st}$, $ldiesel_{st}$, lfr_{1st}, …, lfr_{27st}, *dummy for state* 2_{st}, …, *dummy for state* 10_{st}, *dummy for year* 2002_{st}, …, *dummy for year* 2017_{st}, *trend for state* 1_{st}, …, *trend for state* 9_{st}), as we do not include dummy variables for state 1 (Bahia), year 2001, and trend variable for the state of São Paulo to avoid perfect collinearity. This vector is exogenous (i.e. from our conceptual model $E(\mathbf{w}_{st}' u_{stg}) = 0$ for each structural equation g = 1, 2, 3).

TABLE 3 Variable list and descriptions.

Variable	Description	Source[a]
demand	Agricultural total production in million tonnes - IBGE defines criteria and performs the conversions of different production measures (e.g. 1000 bunches and 1000 fruits) to tonnes	A
acreage	Agricultural acreage in million hectares, as agricultural total planted area	A
yield	Agricultural land yield in tonnes per hectares, as the agricultural total production over agricultural acreage	A
ipca	The extended national consumer price index deflated by IGP-di from FGV, as deflated IPCA - *Índice Nacional de Preços ao Consumidor Amplo* that measures the variation in the living cost of families whose head is salaried with monthly income between 1 and 40 Brazilian minimum monthly wages	A
gnppc	Gross national product (GNP) per person in R$, as each state GNP over its estimated resident population	A, B
ownprice	Agricultural price in R$ per tonne, as the agricultural production value over the agricultural total production	A, B
ppi	Prices paid by rural producers index deflated by IGP-di from FGV with year 2017 = 100, generated by FGV according to monthly surveys of prices paid by farmers for seeds, fertilisers, fuels, labour and machine hours	B
fedcattle	Fed cattle price in R$ per arroba of 15 kilograms	B, C
steer	Feeder steer price in R$ per head	B, C
diesel	Diesel fuel price in R$ per litre	B, D
fr_i, i = 1, …, 27	Market equilibrium freight rates from the 10 biggest Brazilian agricultural producer states to destination state *i* in R$per tonne per km	B, E
trend	Time trend, receives 1 in year 2001, 2 in year 2002 and so on	

[a] A—Municipal Agricultural Survey of the Brazilian Institute of Geography and Statistics (PAM / IBGE) through the Brazilian Institute of Geography and Statistics (IBGE) Automatic Recovery System (SIDRA); B—FGVDados from Getúlio Vargas Foundation (FGV); C—AgroLink, <https://www.agrolink.com.br/cotacoes/>; D—National Agency of Petroleum, Natural Gas and Biofuels (ANP); E—Freight Information System (SIFRECA) of the Esalq/USP. All monetary values and price indexes are in real terms of year 2017 by the general price index (IGP-di) from Getúlio Vargas Foundation (FGV).

on the included instruments, none of them directly affect the equilibrium agricultural output. However, as a change in any of them shifts the agricultural demand that will change the endogeous variable *lownprice*, they satisfy the relevance condition for an instrumental variable (Angrist & Pischke, 2009; Pearl, 2009). In other words, excluded instruments in Equations (9) and (10) only indirectly affect the equilibrium agricultural output through *lownprice*.

In turn, conditionally on the included instruments, the excluded instruments in Equation (8) (i.e. *lppir*, *lsteer*, *ldiesel* and the 27 freight rates) satisfy the exclusion restriction as none of them directly affect the equilibrium agricultural output. But a change in any of them shifts the agricultural supply that will change the endogenous variable *lownprice*, which satisfies the relevance condition for an instrumental variable. To sum up, the excluded instruments in Equation (8) only indiretly affect the equilibrium agricultural output through *lownprice*.

As we use the same 68 variables as instruments in every equation of the SEM, this makes the generalised method of moments (GMM) with unrestricted weighting matrix, the GMM three-stage least squares (GMM 3SLS), and the traditional 3SLS estimators identical estimation procedures (Wooldridge, 2010).

Since, in our case, T (i.e. number of years) is larger than N (i.e. number of cross-section units), our framework is of multiple time series analysis, wherein N can be held fixed while T goes to infinity (Wooldridge, 2010). In this regard, Pesaran (2015) posits that the multivariate time series analysis of the system of equations with endogenous variables estimated by 3SLS is consistent and converges to a normal distribution for T bigger than a certain number of

TABLE 4 Descriptive statistics of our panel data set—10 Brazilian States from Year 2001 to 2017, 170 observations.

Variable[a]	Mean	Standard deviation	Minimum	Maximum
demand (million tonnes)	73.57	109.19	4.86	481.04
acreage (million hectares)	5.63	3.29	0.69	15.64
yield (tonnes per hectare)	11.82	13.34	2.11	58.08
ipca (year 2017 = 100)	65.41	18.76	35.68	100.00
gnppc (R$ per person)	28,740.65	8404.81	11,322.56	49,384.34
ownprice (R$ per tonne)	590.16	337.22	88.41	1814.78
ppi (year 2017 = 100)	63.45	22.75	16.69	110.45
fedcattle (R$ per arroba)	122.99	16.46	89.57	167.71
steer (R$ per head)	1273.28	267.78	649.79	2222.57
diesel (R$ per litre)	3.16	0.29	2.64	4.03
fr_{ac}	0.15	0.04	0.08	0.27
fr_{al}	0.15	0.04	0.04	0.26
fr_{am}	0.15	0.04	0.04	0.26
fr_{ap}	0.15	0.04	0.05	0.25
fr_{ba}	0.16	0.03	0.11	0.26
fr_{ce}	0.16	0.03	0.11	0.25
fr_{df}	0.17	0.03	0.01	0.27
fr_{es}	0.16	0.04	0.08	0.26
fr_{go}	0.17	0.03	0.09	0.27
fr_{ma}	0.17	0.03	0.11	0.27
fr_{mg}	0.16	0.03	0.09	0.25
fr_{ms}	0.17	0.04	0.11	0.33
fr_{mt}	0.16	0.03	0.11	0.25
fr_{pa}	0.16	0.03	0.11	0.25
fr_{pb}	0.16	0.03	0.10	0.25
fr_{pe}	0.16	0.03	0.10	0.25
fr_{pi}	0.16	0.03	0.11	0.26
fr_{pr}	0.16	0.02	0.11	0.23
fr_{rj}	0.16	0.03	0.10	0.26
fr_{rn}	0.15	0.05	0.05	0.26
fr_{ro}	0.15	0.04	0.06	0.26
fr_{rr}	0.15	0.05	0.05	0.25
fr_{rs}	0.15	0.03	0.08	0.27
fr_{sc}	0.16	0.04	0.11	0.33
fr_{se}	0.16	0.03	0.11	0.25
fr_{sp}	0.17	0.04	0.11	0.28
fr_{to}	0.16	0.03	0.11	0.26

[a]Freight rates are in R$ per tonne per km and their subscripts denote the Brazilian state of destination: ac, Acre; al, Alagoas; am, Amazonas; ap, Amapá; ba, Bahia; ce, Ceará; df, Distrito Federal; es, Espírito Santo; go, Goiás; ma, Maranhão; mg, Minas Gerais; ms, Mato Grosso do Sul; mt, Mato Grosso; pa, Pará; pb, Paraíba; pe, Pernambuco; pi, Piauí; pr, Paraná; rj, Rio de Janeiro; rn, Rio Grande do Norte; ro, Rondônia; rr, Roraima; rs, Rio Grande do Sul; sc, Santa Catarina; se, Sergipe; sp, São Paulo; to, Tocantins. All monetary values and price indexes are in real terms of year 2017 by the general price index (IGP-di) from the Getúlio Vargas Foundation (FGV).

observations over time if variables are exogenous and their matrix is invertible. These two conditions are satisfied in our case as our conceptual model supports the exogeneity of variables in our SEM, and we can estimate the models by 3SLS such that the matrix of exogenous variables is invertible.

We first estimate the SEM by the traditional 3SLS, using the reg3 procedure in the Stata 15 software. The reg3 procedure uses the closed-form matrix solution for the estimators (StataCorp., 2017; Wooldridge, 2010) but does not allow for state cluster robust variance estimation as an option to fix the inference procedure. Therefore, we estimate the SEM by the GMM 3SLS estimator with robust standard errors to cluster correlation at the state level, using the gmm procedure with the vce (cluster state) option (StataCorp., 2017). Moreover, to estimate our SEM by GMM, we use Equation (9) without lfr_{am}, lfr_{ap}, $lfrb_{a}$, fr_{ms} and lfr_{sc} and Equation (10) without lfr_{mg}, lfr_{pi}, lfr_{pr} ans lfr_{rr} as they are insignificant in the 3SLS estimation. Thus, we save nine degrees of freedom, making it possible to perform the GMM estimation that requires an estimation of a 3×3 matrix of variance between equations (Wooldridge, 2010).

Table 5 reports the SEM estimates by GMM 3SLS equal to those obtained by 3SLS but with state cluster robust standard errors. We interpret SEM estimates in Table 5 as follows.

Table 5 shows GMM 3SLS estimates of the SEM with and without freight rates. However, the SEM with freight rates is preferred as its Bayesian Information Criterion (BIC) value is lower than for the model without freight rates, and freight rates are jointly statistically significant in acreage and land yield equations by the Wald test ($p = 0.000$). Moreover, freight rates should be in our SEM according to the partial equilibrium model in the agricultural composite good and lands markets. Additionally, for the SEM without freight rates, intensive and extensive margin price elasticities are individually insignificant, which is implausible by the theoretical results in Tables 1 and 2. Moreover, the agricultural demand is price elastic, which is unexpected as, for a composite good, there is the possibility of substitution of one commodity for another (Thompson, 1916). Also, the agricultural demand is income elastic, which is not in accordance with the Engel's law for food (i.e. the income percentage allocated for food consumption decreases as income rises). Thus, we only interpret the estimates for the SEM with freight rates in Table 5.

The agricultural demand is price inelastic as its estimate is −0.366 ($p = 0.007$); is income inelastic as its estimate is 0.973 ($p = 0.000$) in line with Engel's law for food; and is homogeneous of degree zero in prices and income ($p = 0.142$) in line with the micro-economic consumer theory. These estimates are also compatible with own price (−0.384) and income (0.704) elasticity estimates of the demand for food, beverages and tobacco provided by Muhammad et al. (2013) from a two-stage cross-country demand system estimation for 144 countries in 2005. Furthermore, the results suggest that the agricultural demand would not respond to cross-prices (i.e. the livestock price *lfedcattle* [$p = 0.574$] and the price of other goods *lipca* [$p = 0.804$]).

The extensive margin price elasticity estimate suggests that agricultural acreage would rise by 2.65% in response to a 10% increase in agricultural price. This estimate is compatible with a 4% rise calculated by Barr et al. (2011) as it is in our 95% confidence interval. The intensive margin price elasticity estimate suggests that agricultural yield would rise by 6.94% in response to a 10% increase in agricultural price. In summary, agricultural supply would rise by 9.60% ($p = 0.000$) in response to a 10% increase in agricultural price, mostly by yield growth that would account for 72.3% of this response.

The agricultural acreage response to a change in the agricultural input price, the summed coefficients of *lppi* and *ldiesel*, is null ($p = 0.122$). Theoretical results in Table 2 indicate that the agricultural yield response to a change in agricultural input price should be negative, as its estimate is −1.820 ($p = 0.014$). Therefore, agricultural supply would decrease by 18.2% in response to a 10% increase in agricultural input price, but only by the mechanism of yield decrease as agricultural acreage would not change.

TABLE 5 Generalised method of moments three-stage least squares estimates of the simultaneous equation model with and without freight rates.

	SEM without freight rates			SEM with freight rates		
Variable	Demand equation (8)	Yield equation (9)	Acreage equation (10)	Demand equation (8)	Yield equation (9)	Acreage equation (10)
lownprice	−1.510***	1.645	−0.045	−0.366***	0.694***	0.265***
	(0.453)	(1.500)	(0.375)	(0.135)	(0.211)	(0.070)
lppi		0.296*	−0.028		0.024	−0.026
		(0.166)	(0.033)		(0.048)	(0.038)
ldiesel		−4.264**	0.584		−1.845**	0.345*
		(2.041)	(0.434)		(0.740)	(0.180)
lfedcattle	0.236	−0.515	0.112	0.096	−0.398	−0.019
	(0.473)	(0.830)	(0.183)	(0.170)	(0.392)	(0.102)
lsteer		0.220	−0.025		0.218	−0.101**
		(0.238)	(0.057)		(0.207)	(0.042)
lipca	−1.361			0.155		
	(1.138)			(0.625)		
lgnppc	1.397***			0.973***		
	(0.290)			(0.160)		
lfr_{ac}					0.323	−0.415
					(0.691)	(0.307)
lfr_{al}					−0.752***	0.452
					(0.246)	(0.314)
lfr_{am}						−0.260
						(0.162)
lfr_{ap}						−1.034***
						(0.387)
lfr_{ba}						−0.206*
						(0.108)
lfr_{ce}					−1.640***	0.725***
					(0.408)	(0.179)
lfr_{df}					0.433	−0.550***
					(0.304)	(0.044)
lfr_{es}					0.135	0.414***
					(0.403)	(0.085)
lfr_{go}					−0.511**	−0.172**
					(0.244)	(0.071)
lfr_{ma}					−1.026	1.297***
					(0.813)	(0.142)
lfr_{mg}					0.157	
					(0.162)	
lfr_{ms}						0.403***
						(0.051)

(Continues)

TABLE 5 (Continued)

Variable	SEM without freight rates			SEM with freight rates		
	Demand equation (8)	Yield equation (9)	Acreage equation (10)	Demand equation (8)	Yield equation (9)	Acreage equation (10)
lfr_{mt}					1.163***	−0.021
					(0.229)	(0.105)
lfr_{pa}					−2.698***	0.965***
					(0.720)	(0.143)
lfr_{pb}					−1.007***	−0.166
					(0.181)	(0.107)
lfr_{pe}					1.502***	0.164
					(0.503)	(0.284)
lfr_{pi}					0.736*	
					(0.382)	
lfr_{pr}					0.201	
					(0.162)	
lfr_{rj}					0.423***	−0.118*
					(0.119)	(0.064)
lfr_{rn}					1.122***	0.173
					(0.400)	(0.113)
lfr_{ro}					0.769**	0.340
					(0.374)	(0.269)
lfr_{rr}					−0.460	
					(0.529)	
lfr_{rs}					−0.132	0.177***
					(0.227)	(0.047)
lfr_{sc}						0.152**
						(0.077)
lfr_{se}					1.352	−1.632***
					(0.836)	(0.296)
lfr_{sp}					−0.385	−0.248***
					(0.299)	(0.049)
lfr_{to}					0.324	−0.485**
					(0.585)	(0.192)
Intercept	20.599	105.859	45.674**	77.077***	88.151	10.880
	(25.343)	(103.572)	(23.169)	(7.081)	(54.442)	(10.536)
Observations	170	170	170	170	170	170
R-squared	0.988	0.924	0.995	0.996	0.982	0.998
Bayesian information criterion (BIC)	−390.4			−630.6		

Note: *, ** and *** denote the significance at the 10%, 5% and 1% levels. Robust standard errors to cluster correlation at state level appear in parentheses.

As the agricultural acreage response to a change in livestock price *lfedcattle* is null ($p=0.856$), the response of the agricultural land yield to a change in the livestock price is null ($p=0.310$) in line with theoretical results in Table 2. In fact, agricultural supply would not respond to a change in livestock price ($p=0.349$).

The agricultural acreage response to livestock input price *lsteer* is individually significant. However, as agricultural supply ($p=0.586$) and agricultural yield ($p=0.292$) responses to livestock input price are both individually null, the agricultural acreage response to livestock input price is in fact null in line with results in Table 2.

As data on freight rates of the agricultural and livestock goods are the same, individual signals of coefficients, $\beta_{72}, \ldots, \beta_{332}$ in Equation (9) and $\beta_{73}, \ldots, \beta_{333}$ in Equation (10), cannot be anticipated based on theoretical results in Tables 1 and 2. The reason for this is that each of these coefficients is the sum of agricultural and livestock freight rate elasticities of the agricultural yield and the acreage. However, as the agricultural freight rate elasticity of the agricultural acreage is necessarily negative by results in Table 1, a non-negative freight rate elasticity of agricultural acreage implies that the livestock freight rate elasticity of the agricultural acreage is positive. As this is the case for states of Ceará, Espírito Santo, Maranhão, Mato Grosso do Sul, Pará, Rio Grande do Sul and Santa Catarina, a freight rate increase to one of them would make agriculture less profitable than livestock activity, such that land would switch from agriculture to livestock activity. These results suggest that agriculture does compete for land with livestock; notwithstanding, we have found that agricultural acreage does not respond to livestock input and output prices.

Estimation from Equations (6) and (7) suggest that a 10% exogenous growth in demand (i.e. $\Delta_A^D=10$) gets translated into a 7.54% rise ($p=0.000$) in equilibrium agricultural price; a 2% rise ($p=0.001$) in equilibrium agricultural land use; and a 7.24% rise ($p=0.000$) in equilibrium agricultural output. Thus, Brazil's agriculture would satisfy most of the demand growth by expanding equilibrium agricultural output mainly through yield increase.

Finally, estimation from Equations (6) and (7) suggest that a 5% exogenous decrease in agricultural yield and arable land for agriculture (i.e. $\Delta_L^S-\Delta_L^D=5-(-5)=10$) caused by an adverse climate shock would be translated into a 7.54% rise ($p=0.000$) in equilibrium agricultural price; a 3% decrease ($p=0.000$) in equilibrium agricultural land use; and a 2.76% decrease ($p=0.007$) in equilibrium agricultural output. Thus, Brazil's agriculture would offset most of the adverse climate shock in supply, with only marginal reduction in agricultural output. The mechanism mostly works through increasing the yield on land that stays in agriculture.

5 | POLICY IMPLICATIONS

Using estimates in Table 5, we provide two examples of road infrastructure policies that may be implemented to neutralise shocks in demand for food, fibre, fuel and arable land area in Brazil.

Estimates suggest that a road infrastructure policy that reduces freight rate to diminish the market equilibrium agricultural land use, while maintaining equilibrium agricultural price and output, is feasible if it focusses on the states of Espírito Santo, Maranhão and Rio Grande do Sul. The reason being that estimates of the freight rate elasticity of the agricultural acreage are positive, and the corresponding estimates of agricultural supply are null for those destination states. For example, a 10% freight rate reduction to Maranhão[2] would decrease equilibrium agricultural land use by 12.97% (i.e. $\Delta_L^S=12.97$), while increasing agricultural land yield by 12.97% (i.e. $\Delta_L^D=12.97$). These policy-induced changes would consequently decrease

[2]The Port Complex of Maranhão is the largest in Brazil, and its Itaqui port is the best logistic option for the Central-North corridor, which is responsible for 45% of Brazil's grain production.

equilibrium agricultural land use by 12.97%, while keeping the equilibrium agricultural price and output unchanged. Hence, such a policy could be utilised to neutralise an exogenous shock that reduces arable land area by 12.97%.

Estimates also suggest that a road infrastructure policy that reduces freight rate to increase equilibrium agricultural output, while diminishing equilibrium agricultural price and land use, is feasible if the policy focusses on the states of Pará and Ceará. The reason being that estimates of the freight rate elasticity of the agricultural acreage are positive, and estimates of the freight rate elasticity of the agricultural supply are negative for those destination states. For example, a 10% freight rate reduction in the state of Pará[3] would decrease agricultural land use by 9.65% (i.e. $\Delta_L^S = 9.65$) and would increase agricultural land yield by 26.98% (i.e. $\Delta_L^D = 26.98$). Those policy-induced changes would decrease equilibrium agricultural price by 27.63% ($p = 0.000$) and equilibrium agricultural land use by 7.33% ($p = 0.021$), and increase equilibrium agricultural output by 10.10% ($p = 0.000$). As $\Delta_L^D - \Delta_L^S = 17.33$, those policy-induced changes could neutralise an exogenous demand growth of 17.33% (i.e. $\Delta_A^D = 17.33$), as they would maintain equilibrium agricultural price and output, while market equilibrium agricultural land use would decrease by 9.65% ($p = 0.000$). In other words, such a policy could be put in place to neutralise a shock that combines an agricultural demand growth of 17.33% and a reduction of 9.65% in arable land area.

Hence, road infrastructure policies can be designed for freight rate reduction in some specific destination states to offset shocks in demand for food, fibre and fuel, and in land yield and arable land area.

6 | SUMMARY AND CONCLUSIONS

Brazil is one of the largest export-oriented agricultural economies in the world; however, it still preserves 66.3% of its native vegetation land. As such, Brazil is expected to play a key role in expanding agricultural output, while preserving native vegetation to dampen long-term agricultural price escalation under the scenario of growing global demand for food, fibre and fuel and adverse climate shocks. This study assesses the responsiveness of equilibrium agricultural output, price and land use to shocks and provides suggestions for road infrastructure policies in Brazil towards offsetting the consequences of those shocks.

Prior empirical work on agricultural demand and supply has primarily focussed on specific or groups of crops, estimating either only acreage price response under the assumption of insignificant land yield response or only total agricultural supply price elasticity for Brazil. There has been a tendency to ignore that agricultural price is simultaneously determined by supply and demand. Additionally, freight rates have not been included in the analyses, despite their significance, especially in large countries such as Brazil, Australia, the United States or Canada. This has possibly led to inconsistent estimation due to price endogeneity and omission of variables.

This study closes these gaps in the literature as we estimate an SEM composed of demand, land yield and acreage equations for a single agricultural composite good. This makes it possible to jointly estimate demand, land yield and acreage price elasticities, and test hypotheses on the responsiveness of the market equilibrium for agricultural output, price and land use to shocks in Brazil. Furthermore, we include freight rates, state and time fixed effects, state-specific time trends and estimate the SEM by the GMM 3SLS method to overcome inconsistent estimation procedures arising from the omission of variables and price endogeneity in prior studies. We do so with the use of robust standard errors to cluster correlation at the state level to fix the statistical inference procedures, using a panel data set of the 10 biggest agricultural producer states in Brazil from 2001 to 2017. All is undertaken based on a partial equilibrium

[3]The complex port of Pará is one of the largest in Brazil as comprises the ports of Belém, Vila do Conde, Santarém, Óbidos, Itaituba and Altamira.

model in the agricultural composite good and lands markets that we used to guide the specification and estimation of the SEM, and for which we connect Hertel's (2011) closed forms of equilibrium agricultural output, price and land use responsiveness to exogenous shocks. Our framework may guide similar studies for other countries and regions.

We find that Brazil's agriculture is expected to respond to exogenous growth in demand, satisfying most of it by expanding equilibrium agricultural output from a small land use rise that creates little additional pressure on native vegetation, as equilibrium land yield substantially increases.

Our results also suggest there is a significant opportunity to design road infrastructure policy in Brazil that combines freight rate reductions in specific destination states (e.g. Maranhão and Pará) to offset exogenous shocks in agricultural demand, land yield and arable land area. Therefore, the road infrastructure policy may play a role in offsetting exogenous shocks in Brazil's agricultural sector, which should be assessed by similar studies for other countries and regions.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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