UMA ABORDAGEM ECONOMÉTRICA PARA A AVALIAÇÃO DE CARBONO NO CINTURÃO CITRÍCOLA BRASILEIRO
AN ECONOMETRIC APPROACH TO CARBON VALUATION IN THE BRAZILIAN CITRUS BELT

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Resumo
Métodos de precificação do carbono como o custo social do carbono (CSC) e o custo marginal de abatimento (MAC) constituem instrumentos crescentemente adotados pelas economias para valorar as emissões de gases de efeito estufa. Esse trabalho tem o objetivo de precificar o carbono na citricultura brasileira, especificamente no setor de laranja, por meio de uma modelagem econométrica. Considerou-se a especificação de um modelo com erro autorregressivo espacial para os municípios representativos da cadeia citrícola do estado de São Paulo e da região Sul de Minas Gerais, onde se concentra aproximadamente 85% da produção brasileira. No total, a análise envolveu 297 municípios brasileiros produtores de laranja, sendo 274 municípios em São Paulo e 23 em Minas Gerais. Contudo, o número de municípios reduziu-se para 111 quando a variável energia renovável foi incluída na análise. O valor do carbono na citricultura foi de USD7.88/tCO2e a preços de 2021 com a inclusão dessa variável. Os resultados mostraram associações positivas entre produto interno bruto (PIB) municipal, área territorial, emissões de carbono na citricultura com o preço do carbono. Por outro lado, a participação da agricultura no PIB e a produção de energias renováveis relacionaram-se negativamente ao nível de preços.
Palavras-chave: precificação do carbono, custo social, custo de abatimento.

Abstract
Carbon pricing methodologies, such as the Social Cost of Carbon (SCC) and the Marginal Abatement Cost (MAC), are increasingly used by economies to value greenhouse gas emissions. The objective of this study is to price carbon in the Brazilian citrus industry, specifically in the orange sector, through econometric modeling. It considered the specification of a model with spatial autoregressive errors for the representative municipalities of the citrus chain in the state of São Paulo and the southern region of Minas Gerais, where approximately 85% of Brazilian production is concentrated. In total, 297 Brazilian orange-producing municipalities were included in the analysis, of which 274 were in São Paulo and 23 in Minas Gerais. However, the number of municipalities was reduced to 111 when the renewable energy variable was included in the analysis. The value of carbon in citriculture was USD7.88/tCO2e at 2021 prices with the inclusion of this variable. The results showed positive associations between municipal gross domestic product (GDP), land area, citrus carbon emissions, and carbon price. On the other hand, the share of agriculture in GDP and renewable energy production were negatively related to the price level.
Key words*: carbon pricing, social cost of carbon, abatement cost.*

1. Introduction

Carbon pricing is an important support mechanism in the process of decarbonizing economies (RFF & NYSERDA, 2020; Ricke et al., 2018). The pricing approaches and methodologies are used in conformity with mandatory or voluntary policies through which the environmental costs of greenhouse gas emissions can be included in the economy. Being one of the major players in the agriculture sector, citrus farming has been seen to experience some significant obstacles, including ensuring environmental sustainability and reducing carbon emissions. The adoption of a carbon pricing system by the citrus industry is critical because it will help address these challenges and also foster supply chain sustainability.

The citrus sector includes, in addition to the production of oranges, the main products of the chain: mandarins, sour limes and lemons. The importance of the citrus market configuration to the Brazilian economy extends to a global level, placing Brazil as the second largest citrus producer in the world (behind China) (Vidal, 2021) and the largest global producer of oranges and orange juice, with a production of 16,214,982 tons in 2021 (IBGE, 2022). The orange sector is very important in terms of its contribution to the Brazilian economy. It was the second largest permanent agricultural sector in 2021, generating USD2.4 billion of gross value added, which corresponds to 14% of the total gross value added by permanent crops (IBGE, 2022). This study emphasizes the orange sector, especially as a result of the project "Orange growers participation in carbon stock dynamics and biodiversity preservation", developed as a partnership between two Brazilian institutions, Embrapa Territorial and Fundecitrus (Fund for Citrus Protection), and supported by the Farmer Innovation Fund of the British company Innocent (EMBRAPA, 2022a).

The orange sector is not a high CO2 emitter in comparison to other fruit sectors such as strawberry. Mordini, Nemecek e Gaillard (2009) showed that the emission rate in Brazilian citriculture is 160 kg CO2/ton of fruit (agricultural stage). In Brazil, there are few initiatives to quantify carbon emissions at the agricultural stage. Similarly, there is no empirical literature specifically focused on pricing carbon for orange orchards in the country.

Estimates of price of carbon are typically conducted using integrated assessment models (IAMs), such as the dynamic integrated climate–economy (DICE) model, the regional integrated climate–economy (RICE) model, and the climate framework for uncertainty, negotiation and distribution (FUND) model, and analyses involving the development of marginal abatement cost (MAC) curves. Among the variables included in these analyses are those related to economic growth, population, and technological change, from which emission trajectories are defined and translated into climate (Alatorre *et al.*, 2019). However, the vast majority of price of carbon estimates use a combination of one or more models because the relationship between the price of carbon and others variables can be complex. In Brazil, Gurgel e Laurenzana (2016) conducted a study with a dynamic and integrated approach to carbon pricing in Brazilian agriculture, projecting this value to 2030.

This work aimed to estimate the price of carbon in Brazilian citriculture, specifically in the orange sector (agricultural stage), based on two approaches widely used in the literature on the subject, namely, the social cost of carbon and the marginal abatement cost (MAC) approach. Based on the carbon values previously presented by Gurgel e Laurenzana (2016), and considering the variables commonly addressed in the literature on the social cost of carbon (SCC) and the marginal abatement cost (MAC), this study developed a spatial econometric model for the states of São Paulo (SP) and Minas Gerais (MG) in Brazil. These two regions account for 85% of the Brazilian orange production in 2021 (IBGE, 2022b). In addition to estimating an average value for carbon in the Brazilian citrus industry, the results obtained are relevant because they take into account the spatial interdependencies that may occur between carbon pricing and variables such as municipal GDP and CO2e emissions.

2. Theoretical background

Although most of the research done on carbon pricing concerns the impact of carbon pricing on the economy, it is usually considered from a perspective aimed at investigating whether carbon pricing policies can be efficient in cutting emissions and supporting the transition towards a low-carbon economy (Dumortier; Elobeid, 2021; Stepanyan *et al.*, 2023). However, understanding how economic and environmental variables affect the price of carbon is essential for a comprehensive approach to climate policy. In this sense, integrated assessment studies and carbon abatement curve analyses are crucial for the implementation of effective climate change mitigation strategies.

Typically, estimates of the social cost of carbon (SCC) have been calculated using integrated assessment models (IAMs) that aim to incorporate environmental externalities. The social cost of carbon (SCC) is a measure that offers financial evaluations of future environmental and social consequences resulting from rises in greenhouse gas (GHG) emissions within a specific timeframe. It represents the total impact of an extra ton of CO2e on climate change, encompassing effects on agriculture, health, damage to property, and ecosystem services. Calculations in SCC require choosing a discount rate to evaluate costs and benefits happening at various time points. Pioneering works in this area have been done by Nordhaus (2020, 2017). The model incorporates losses associated with climate change impacts by using damage costs, which are influenced by emissions from economic activities based on a damage function. The key determinants of the price of carbon in these approaches include the level of GDP, CO2 emissions, the share of agriculture in GDP, population, energy, land, urbanization rate, and temperature change (Anthoff *et al.*, 2011; Dayaratna; McKitrick; Michaels, 2020; Han; Chen, 2022; Nordhaus, 2020).

SCC studies have been conducted globally with a sectoral decomposition that includes agriculture. Using the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model, Anthoff et al. (2011) found that the distribution of the social cost of carbon by sector varies with the rate of time preference in a study covering 16 global regions between 2010 and 2019. At a rate of 0.1%, agriculture accounts for 68% of the harmful marginal impact, while cooling energy contributes 27%. Conversely, at a 1% rate, cooling energy accounts for 64% of the detrimental marginal impact, while agriculture accounts for 21%. At a 3% rate, agriculture and cooling have similar magnitudes but opposite signs: -USD6.5/tCO2e and USD6.8/tCO2e, respectively.

The same model was also used by (Dayaratna; McKitrick; Michaels, 2020) to examine the implications of recent empirical evidence on CO2 fertilization and climate sensitivity for the estimation of the social cost of carbon (SCC) within the FUND model. Using a ten-year discount rate of 3%, the average SCC increased from USD19.33 to USD27.06 per ton of CO2 between 2020 and 2050. When choosing parameters for IAM models, researchers must decide on the most appropriate assumptions. Thus, depending on the choice of a given discount rate, then the SCC will be relatively small compared to 2.5% or 3% cases.

Other integrated models focusing on carbon pricing for agriculture have been proposed using an agent-based approach Bakam, Pajot e Matthews (2012) to estimate price of carbon from a closed-loop emissions trading system in the agricultural sector. Model simulations indicate that while the price of carbon escalates significantly with reduction targets, the implementation of an emissions trading system could lead to substantial emission reductions at a reasonable cost. Emissions reductions of up to 12% could be achieved at a price of less than £25.5/CO2e (USD50/tCO2e) in 2007.

Moore et al. (2017) introduced damage functions derived from current scientific literature into an integrated model to calculate an updated social cost of carbon (SCC) in agriculture. The authors used the GTAP computable general equilibrium model to calculate the economic consequences of production shocks between 1997 and 2012. The updated damage functions show significantly larger negative impacts on agriculture than those currently included in Integrated Assessment Models (IAMs). Agricultural impacts shift from net benefits of USD2.7/tCO2e to net costs of US$ 8.5/tCO2e, more than doubling the total social cost of carbon (SCC).

Despite efforts focused on integrated assessments for carbon pricing, the majority of studies on GHG mitigation costs in agriculture emphasize a bottom-up approach, with a particular emphasis on Marginal Abatement Cost (MAC) analysis. The MAC approach provides monetary estimates of GHG emissions based on the marginal abatement cost of achieving emission reduction targets, which represents the cost of abating a marginal unit of GHG at the lowest cost to society (RFF; NYSERDA, 2020). Studies using agricultural MAC curves typically include the cost of implementing technologies (Ahmed, 2020; Eory *et al.*, 2018) and the inputs used in the process, such as labor, capital, land, and energy (Gillingham; Stock, 2018). Biophysical processes are often addressed and include a variety of natural factors and processes as determinants of costs associated with carbon emissions in agriculture. Some of these determinants include fertilizer and pesticide use, farm machinery use, land productivity, and irrigation (Wang *et al.*, 2014; Wang, 2015). Crop and feedstock MAC curves have also been developed to compare CO2 mitigation technologies for these segments, such as in (Sapkota *et al.*, 2019).

It is also worth highlighting studies that calculate the shadow price of agricultural carbon, typically using techniques involving the directional distance function. This price serves as a measure of the social cost of damages caused by carbon emissions, providing a parameter for internalizing the environmental costs of these emissions and guiding carbon pricing policies. Notable works in this regard include those by Yamamoto et al. (2022), who estimated the price of carbon in agriculture in Vietnam in 2016 (USD 14.47/t CO2), and Tang, Wang e Zhou (2021) for agriculture in Australia between 2006 and 2013 (A$17.60/tCO2 in 2013 or USD15.68/tCO2).

In Brazil, few studies have focused on carbon pricing in agriculture, and none are specific to the citrus sector. Three important studies with some reference to carbon pricing in agriculture stand out. One of these was conducted by Gurgel e Laurenzana (2016), who developed a quantitative exercise using a computable general equilibrium model to assess the economic costs of implementing mitigation technologies in agriculture. Based on the Emissions Prediction and Policy Analysis (Eppa) model, the authors found that for the crops sector, a price of carbon of USD0.25/tCO2e would result in a reduction of 16 million tons (Mt) of CO2e, which adequately reflects the increased use of direct planting. On the other hand, for the livestock sector, a reduction of 104 Mt CO2e was observed at a price of carbon of USD7.85/tCO2e. Credit resources from the Low Carbon Agriculture Program (ABC) in Brazil between 2010 and 2016 helped reduce losses in production value, resulting in lower greenhouse gas (GHG) mitigation costs. However, even with the support of the program, the livestock sector's difficulty in reducing emissions resulted in higher mitigation costs compared to crops.

Gouvello (2010) study examined the transition to a low-carbon economy in Brazil, with a particular focus on the agricultural sector. The study examined how the country could reduce its GHG emissions while promoting sustainable economic growth, with a focus on agricultural practices. By analyzing marginal abatement cost curves for technologies in different sectors for the period from 2010 to 2030, the study identified a reduction of 302 million tons of CO2e at a cost of USD6/tCO2e, resulting from combined practices of reducing deforestation and intensifying livestock production. This result suggests that implementing these measures could be an effective strategy for mitigating GHG emissions in the agricultural sector.

Finally, another study providing abatement cost estimates for agriculture in Brazil was conducted by McKinsey & Company (2009). The company has been a pioneer in conducting detailed abatement cost studies for various GHG mitigation technologies. In Brazil, the main agricultural activity contributing to greenhouse gas (GHG) emissions is cattle raising, mainly due to enteric fermentation and residues deposited on pastures. The average marginal abatement cost of initiatives in the agricultural sector is low, around €2/tCO2e. These initiatives mainly involve small changes to current agricultural practices and require minimal investment. However, there are barriers to implementing these initiatives, mainly due to the highly fragmented structure of the agricultural sector. In many regions, agriculture is primarily subsistence-based, which reduces its responsiveness to climate change incentives. As a result, using climate change as a driver for action may prove ineffective in these circumstances.

3. Methodology

3.1 Data structure

In this paper, some variables that were selected have been addressed in previous studies on pricing using SCC and marginal abatement cost (Anthoff *et al.*, 2011; Gillingham; Stock, 2018; Han; Chen, 2022; Nordhaus, 2020). First, regarding the explanatory variable 'price of carbon', the specialized literature provided the parameters for calculating this indicator, since there are no carbon values for the citrus sector in Brazilian municipalities. Therefore, based on the average price of carbon for agricultural crops (USD0.25/tCO_2e) and livestock (USD7.85/tCO_2e) provided by Gurgel and Laurenzana (2015) for the period 2015-2030, a value of USD4.55/tCO_2e was obtained. This value was deflated to 2021 using the General Price Index (IGP-DI) measured by the Getulio Vargas Foundation and projected to 2030, in order to maintain the analytical structure proposed by these authors. Thus, after deflation, the value used in this study as a parameter for carbon pricing in Brazilian municipalities was US$7.0/t$CO_2$e. This value was multiplied by the amount of carbon emissions (tCO_2e) of each municipality to obtain the price of carbon in USD/tCO_2e.

The explanatory variable 'municipal GDP (Gross Domestic Product)' was extracted from the IBGE National Accounts website (IBGE, 2020) for the most recent year available (2020) and was converted in USD. The data series was monetarily corrected for 2021 according to the IGP-DI and converted to USD. The exchange rate for the conversion was 5.2 reais per dollar.

The 'territorial area of the municipalities', measured in km^2, was provided by the Brazilian Institute of Geography and Statistics for 2021 (IBGE, 2021). The areas were calculated by the Institute using a geographic information system and the Albers equal-area conic projection.

The 'share of agriculture in the GDP' of each municipalities was obtained by dividing the gross value added by agriculture, also obtained from the National Accounts, by the GDP of the municipalities (IBGE, 2020). The initial value was obtained for 2020 and was also monetarily updated according to the IGP-DI for 2021.

Regarding the 'carbon dioxide emissions' of the citrus sector, measured in tCO_2 per capita, we used the technical coefficient for Brazil (0.16 kgCO_2e/kg of fruit or 160 kgCO_2/ton of fruit) noted by Mordini et al. (2009) in their research on the carbon footprint of citrus and strawberries in different economies[1]. The CO_2 emissions in this work were from the agricultural phase of the orange production chain. Internationally, the indicator used in this study is close

[1] An important initiative to quantify and monitor CO2 emissions from different sectors, including agriculture in Brazil, is the System for Estimating Emissions and Removals of Greenhouse Gases (SEEG), coordinated by the Climate Observatory. However, until this research was completed, there was no information in the system to analyze the citrus sector.

to that of Heller (2017), who estimated the CO_2 emissions from agricultural production at 170 $kgCO_2$/ton of fruit. Thus, the productivity for oranges and the area harvested were obtained from the IBGE Municipal Agricultural Production Survey for 2021 (IBGE, 2022). The total emissions were then divided by the population of each municipality to obtain the CO_2 emissions per capita.

For the explanatory variable 'environmental preservation', measured in hectares, the sum of permanent preservation areas (PPAs), legal reserves and surplus vegetation was calculated for the municipalities in 2021 (SFB 2022). The quantification and characterization of these areas have been systematically determined by Embrapa Territorial (EMBRAPA, 2022a) based on data from the Rural Environmental Registry (CAR) of the Brazilian Forest Service (SFB, 2022).

Finally, the 'energy' variable refers to the power (in kW) of operational renewable energy plants (hydro, biomass, wind and solar). If the plant was no longer operational, then the last operational power reported by the plant was used. The information was obtained from ANEEL's (National Electric Energy Agency) generation information system for April 2022 (ANEEL, 2022).

3.2 Characterization of the samples

Figure 2 illustrates the Brazilian citrus belt, a region composed of the main orange producers in Brazil according to Fundecitrus (2023). It comprises 336 municipalities that account for 85% of the national orange production.

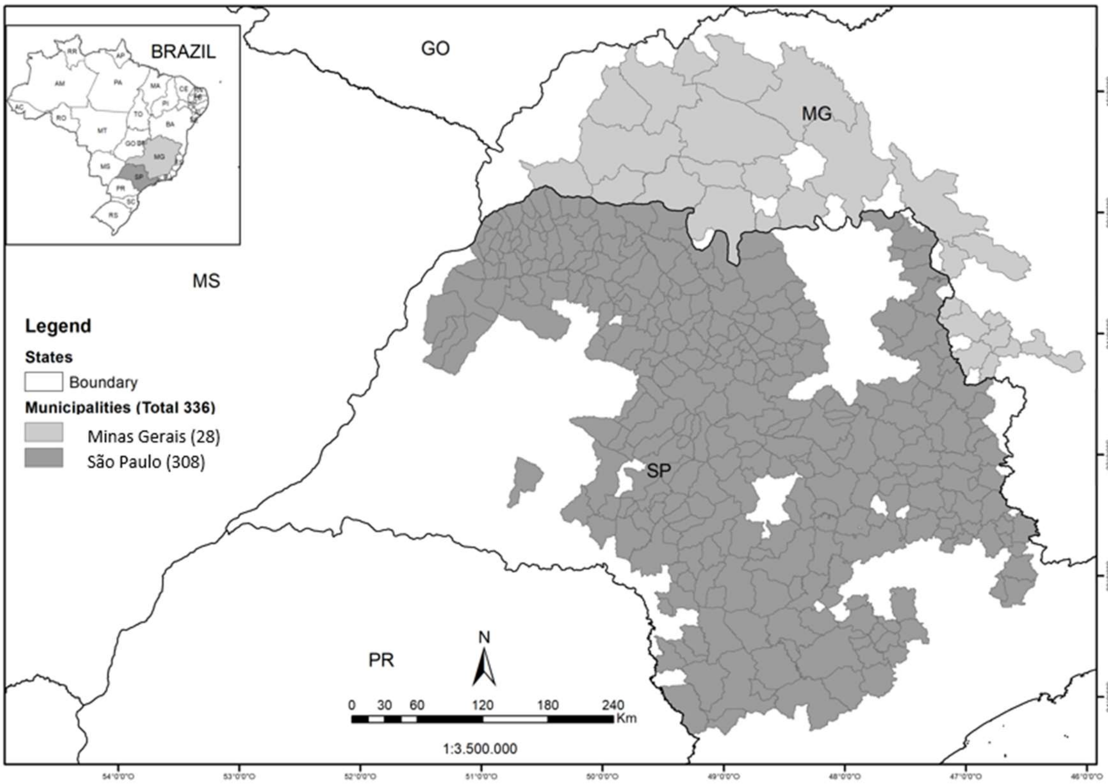


Figure 2 - Citrus belt in Brazil
Source: Fundecitrus (2023).

The number of municipalities considered in this study was slightly lower than that in Figure 2 because the information was not available for the entire citrus belt. Table 1 contains a characterization of the analyzed municipalities. The first sample was composed of 297 municipalities, 23 of which were in Minas Gerais and accounted for a harvested area of 23,507 hectares in 2021. In the same year, the GDP of these municipalities was USD84.0 billion, and agriculture accounted for 24.8% of this total. In São Paulo, the number of municipalities was 274, and the harvested area was 15 times larger than that of Minas Gerais. With a municipal GDP of USD468 billion in 2021, agriculture represented 18.5% of this total. Taking into account the harvested areas and orange productivity in each municipality and using the technical index of 160 $kgCO_2$/ton of fruit provided by Mordini et al. (2009), we found that CO_2e emissions in Minas Gerais would be 19.7 times lower than in the state of São Paulo. The environmental preservation area, according to CAR, in Minas Gerais was 2.2 times smaller than that in São Paulo.

Table 1 - Characterization of citrus-growing municipalities in the states of São Paulo and Minas Gerais.

Sample characteristics	Sample 1 297 municipalities		Sample 2 111 municipalities	
	MG	SP	MG	SP
Number of municipalities	23	274	15	96
Area harvested with oranges (hectares) in 2021	23,507	350,553	13,239	169,004
CO_2 equivalent emissions (thousand tCO_2e)	103,415	2,038,959	57,073	947,860
Total renewable energy capacity (thousand kilowatts) - April 2022*	2,414	4,381	2,413	4,380
Total environmental preservation area registered in CAR (hectares) in 2021**	773,201	1,775,969	536,380	841,220
Total GDP of the municipalities (thousand USD) in 2021***	84,024,171	468,047,944	79,617,234	234,376,154
Gross value added of agriculture/average municipal GDP in 2021 *** (%)	24.8%	18.5%	19.4%	12.5%

Source: Authors' calculations based on Gurgel and Laurenzana (2016), ANEEL (2022), IBGE (2022), IBGE (2021), IBGE (2020), SFB (2021).
* Power from operational plants (renewable energy) in each municipality authorized by ANEEL.
** Area of environmental preservation in the Brazilian Rural Environmental Registry – CAR – (PPAs, legal reserve and surplus vegetation) in 2021.
*** Monetary values were deflated by the Getulio Vargas Foundation's General Price Index (IGP-DI).

In Sample 2, which consisted of 111 municipalities, 15 in Minas Gerais and 96 in São Paulo, the 'renewable energy' variable was included, which reduced the sample size since not all municipalities were energy producers. In Minas Gerais, the total municipal GDP was USD79.6 billion, while the harvested area in 2021 was 13,239 hectares. In São Paulo, where the total municipal GDP was USD 234.3 billion, a harvested area of 169 thousand hectares was verified in 2021. The CO_2e emissions were 947.8 million tons, 16.6 more than in the state of Minas Gerais, and the environmental preservation rate according to CAR in Minas Gerais was 1.6% lower than in São Paulo. Total renewable energy production was 2.4 million kW in Minas Gerais and 4.4 million kW in São Paulo.

The samples were logarithmically transformed to normalize the data. In both models, the standard deviation of the observations was found to be particularly high for CO_2e emissions per capita, given the differences in harvested area and yield of orange groves. The high standard deviation was due to the inclusion of a large number of orange-producing municipalities, ranging from municipalities with low citrus production to municipalities with high citrus production. In 2021, the average value of municipal CO_2 emissions was 192.6 tCO_2e per capita for the sample with 297 municipalities and 167.1 tCO_2e per capita for the sample with 111 municipalities. The standard deviation was also high for GDP and territorial extent due to the different levels of economic development and size of the municipalities.

3.3 Econometric strategy

First, a linear regression was estimated considering the spatial dependencies that usually exist in border regions (Almeida, 2012), an approach focused on spatial econometrics was adopted so that the ordinary least squares (OLS) estimator was used only as a parameter to generate the matrix of spatial weights.

The price of carbon in each municipality was used as the dependent variable in the multiple regression. The explanatory variables were the GDP of the municipality, the territorial area, the share of agriculture and livestock in the GDP of the municipality, the CO_2e emissions and the environmental preservation within the orange sector in the states of Minas Gerais and São Paulo, assuming that these variables would be correlated with the dependent variable. We also included the 'population' variable; however, this variable showed little statistical significance, while its exclusion brought a better fit to the model.

Then, the 'renewable energy' variable was added to the model, as pointed out in the literature, although the sample size was reduced since not all municipalities are energy producers.

The models initially estimated by ordinary least squares (OLS), composed of 6 (six) variables and 297 observations (I.1) and 7 (seven) variables and 111 observations (I.2), respectively, were calculated as follows:

$$CO_2P = \beta_1 + \beta_2 lnGDPmun + \beta_3\, lnsup + \beta_4\, agro + \beta_5 lntCO_{2\,orange} + \beta_6 lnpreserv + \varepsilon \quad \text{(I.1)}$$

$$CO_2P = \beta_1 + \beta_2 lnGDPmun + \beta_3\, lnsup + \beta_4\, agro + \beta_5 lntCO_{2\,orange} + \beta_6 lnpreserv + \beta_7 lnenerg + \varepsilon \quad \text{(I.2)}$$

These variables are described in Table 2.

Table 2 - Description of the variables used in the models.

Variable	Description
Dependent variable	
CO_2P	Price of carbon in each municipality
Independent variables	
$lnGDPmun$	Natural logarithm of the gross domestic product (GDP) of each municipality in 2021
$lnsup$	Natural logarithm of the area of each municipality in 2021
$agro$	Share of agriculture in the GDP of each municipality in 2021
$lntCO_{2\,orange}$	Natural logarithm of the CO_2e emissions of the orange sector in each municipality in 2021
$lnpreserv$	Natural logarithm of the environmental preservation area (permanent preservation area, legal reserve and surplus vegetation) of each municipality registered in the Rural Environmental Registry (CAR) in 2021
$lnenerg$	Power of operational renewable energy plants (hydro, solar, biomass and wind) in kW in 2022
ε	Random errors with zero mean and variance σ^2

Source: Elaborated by the authors.

Given the existing amplitude between the observations, the sample data were normalized by a logarithmic transformation, which reduced the bias of high extremes and captured the constant elasticity between the independent and dependent variables, i.e., the variation in *lnY* per unit variation in *lnX* (Gujarati, 2006).

Subsequently, the use of spatial econometrics provided a set of parameters that enabled data modeling in the presence of autocorrelation or spatial dependence. The most widely used method to quantify spatial dependence structure is the spatial weight matrix (*W*). Known as the spatial proximity matrix, it shows how the neighborhood relates to each observation, expressing the spatial structure of the data. The first-order queen contiguity matrix was used in both models.

Almeida (2012) discusses the procedures commonly used in modeling:

1. The classical model is estimated using MQO and the weight matrix (W);
2. The Lagrange multiplier (LM) is calculated, taking into account the error (LM_{ε}) and lag (LM_{lag}) values;
3. If both test statistics are not significant, then the MQO model is considered the best specification; otherwise, the next step is conducted;
4. If both tests are significant, then the model for which the test statistic based on the Lagrange multiplier is more significant is selected;
5. If the LM_{lag} test is significant and the LM_{ε} test is not, then the spatial lag (SAR) model is estimated; otherwise, the next step is conducted;
6. If the LM_{ε} test is significant and LM_{lag} is not, then the spatial autoregressive model (SEM) is estimated.

The spatial lag model (SAR) indicates that the dependent variable (Y) is influenced by the average of the values of the dependent variable observed in the neighborhood (W_y), by the values of the exogenous independent variables (X) and randomly by an error term (ε). In the spatial autoregressive error model (SEM), on the other hand, the spatial dependence is residual, characterized by the first-order autoregressive structure of the error term (Equation II). The unmodeled effects cannot be correlated with any of the explanatory variables of the regression (Almeida, 2012).

$$Y = X\beta + \varepsilon = \lambda W\xi + \varepsilon \qquad \text{(II)}$$

Where
Y is the price of carbon
X is the matrix of independent variables and consists of $lnGDPmun$, $lnsup$, $agro$, $lntCO_{2\,orange}$, $lnpreserv$ (694 observations/municipalities) and the inclusion of $lnenerg$ (225 observations/municipalities);
β is the regression coefficient of the independent variables;
λ is the autoregressive coefficient;
ξ is the autoregressive error;
$W\xi$ is the spatial error;
ε is the random error with zero mean and variance σ^2.

The spatial autoregressive error model (SEM) proved to be more appropriate for both the sample made of 694 observations and the set made of 225 observations. According to Almeida (2012), the spatial interaction in the SEM occurs in the residuals due to unmodeled effects that are not randomly distributed in space.

The relationship between price of carbon and the variables analyzed can be complex and vary depending on a number of factors, including government policy, economic sector, and international context. Although there may be feedback between the price of carbon and the other variables, no robust evidence of bidirectionality has been found in the literature. In this case, adding complexity to the model may not provide additional benefits in terms of accuracy or interpretability. Thus, a model such as the one proposed may be sufficient to capture the linear relationship between the variables without overfitting.

4. Results and Discussion

Table 3 presents the results of the regression with normalized data using spatial weights for the cross-sectional data series.

Table 3 - Estimation for the spatial autoregressive error model

Variable	Sample 1 (297 municipalities)		Sample 2 (111 municipalities)	
	Coefficient	P>0.05	Coefficient	P>0.05
$price\ of\ carbon$	-9.14172	0.00000	-9.19354	0.00000
$lnGDPmun$	0.654684	0.00000	0.689827	0.00000
$lnsup$	0.358952	0.00088	0.377085	0.02066
$agro$	-1.21489	0.00000	-1.75995	0.00014
$lntCO_{2\ orange}$	0.965745	0.00000	0.942738	0.00000
$lnpreserv$	-0.102435	0.21977	-0.0465118	0.71605
$lnenerg$			-0.105925	0.00001

Source: Authors' calculations based on (ANEEL, 2022; Gurgel; Laurenzana, 2016; IBGE, 2020, 2021, 2022b; SFB, 2022).

In general, the model obtained a satisfactory fit and was statistically significant. The results for the price of carbon in Brazilian citrus showed that there was no relationship between the price of carbon from citrus and the level of environmental preservation of municipalities, measured in terms of legal reserves and permanent preservation areas. In a market where the supply and demand for carbon credits is incipient or a structured market, the lack of relationship between the price of carbon and the level of environmental preservation in municipalities can be observed. In this context, the absence of a regulated carbon market may result in a lack of clear incentives for producers to adopt environmental preservation practices. Even if reducing CO_2 emissions is beneficial to the environment, without an established carbon market, producers may not be aware of the economic benefits associated with environmental preservation.

The other variables showed significant coefficients at the 5% level. In both samples, the R-squared was approximately 0.9, and the signs of the coefficients had the same direction (positive or negative). Municipal GDP was positively correlated with price of carbon. As this variable increased, the value of carbon tended to be higher. Municipalities with higher GDPs tended to have higher production dynamics, MAC curves and high social costs, mainly due to high emission rates that occurred in the economic development process. However, after reaching a certain level of development, many economies tended to undergo a process of dematerialization, in which carbon emission rates tended to decrease with the increase in GDP (Souza, 2013), with implications for carbon pricing. Relatedly, Table 3 shows that a 1% increase in the level of municipal GDP is associated with a 0.654% increase in price of carbon (sample 1) and a 0.689% increase (sample 2) in citriculture. The positive coefficients for territorial area (0.358 for sample 1 and 0.377 for sample 2) show that municipalities with larger territories tended to have higher MAC curves (Campoli; Feijó, 2022).

Regarding the variable CO_2e emissions per capita, a positive relationship with price of carbon was found. An increase of 1% in CO_2e emissions per capita led to an increase of 0.965% (Sample 1) and 0.942% (Sample 2) in carbon value. This conclusion contradicts the literature on agriculture in general (Bakam; Pajot; Matthews, 2012; McKinsey & Company, 2009). A positive relationship between carbon emissions and the price of carbon indicates that emissions are increasing, possibly due to a lack of economic incentives to reduce them. This suggests that the environmental costs of carbon emissions are not being internalized by the market. The introduction of a regulated carbon market can help internalize these costs by incentivizing emission reductions through carbon pricing.

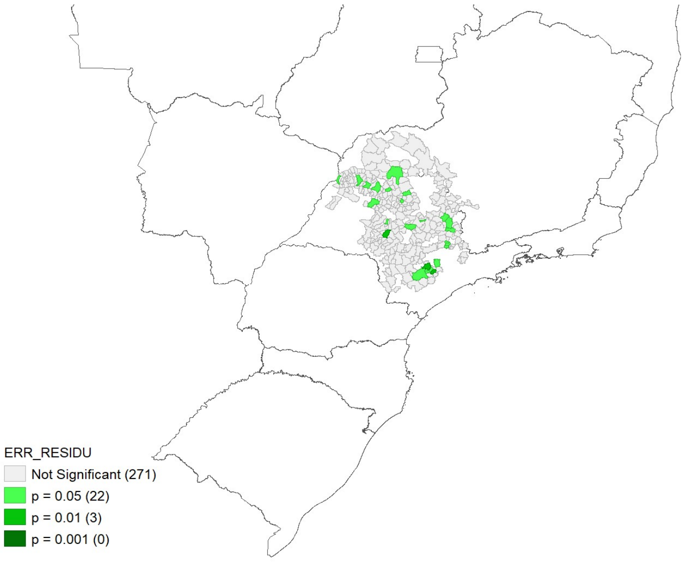
In turn, the production of renewable energy by municipalities was associated with a decrease in the price of carbon. A 1% increase in renewable energy production would result in a 0.1% reduction in this variable. Renewable energy favors the process of decarbonization by reducing CO_2e emissions, but the mitigation costs depend on the type of renewable technology used and may exceed conventional technologies in some cases (Gillingham, 2019).

Finally, the greater the participation of agriculture in GDP was, the smaller the price of carbon, as a 1% increase in this share was associated with a 1.21% decrease in the price of carbon. In municipalities where the agricultural sector plays a larger role in the economy, carbon valuation estimates tend to be lower. In particular, citrus groves consist of evergreen trees that can live for several decades. Unlike annual crops, which require annual land preparation and planting, citrus cultivation may require less soil disturbance over time, which can help reduce CO_2 emissions associated with agriculture. As seen above, a greater reduction in carbon emissions would be associated with a lower price valuation of citrus.

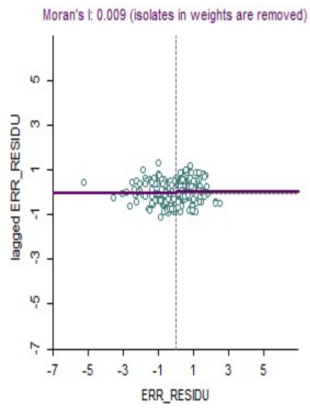
A graphical analysis of the residuals enabled an evaluation of the quality of the regression fit after using the logarithmic function. Figure 3 shows the maps of the standardized residuals (Figures 3.a and 3.c) generated by the spatial autoregressive error models and the corresponding Moran's index (Figures 3.b and 3.d). Values close to 1 indicate positive spatial autocorrelation, and values close to -1 indicate negative spatial autocorrelation. No significant clusters were detected for the residues; i.e., there was no high concentration of residues in any particular part of the map, and there was no spatial autocorrelation. Moran's index for the residuals was 0.009 (Sample 1) and -0.005 (Sample 2), indicating that the residuals were randomly distributed, without a trend, and adequately adjusted for the type of spatial regression.

Sample

Residual Map (a)

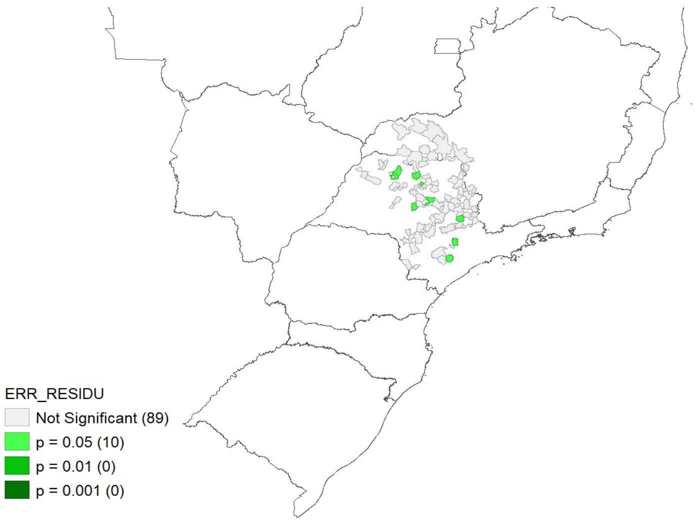


Moran's Index (b)



Sample 2

Residual Map (c)



Moran's Index (d)

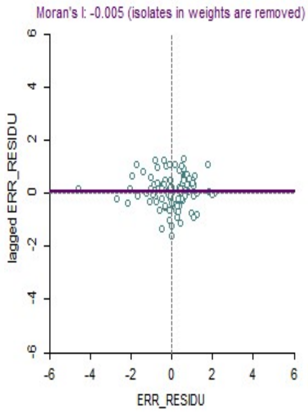


Figure 3 - Residual clustering map and Moran's index
Source: Authors' calculations based on (ANEEL, 2022; Gurgel; Laurenzana, 2016; IBGE, 2020, 2021, 2022b; SFB, 2022).

An exploratory analysis of the data was carried out using the local bivariate Moran index, which indicates the degree of linear association between the value of one variable in a given location and the average of another variable in neighboring locations (Anselin, 2005). Our intention was to test if there was a spatial relationship between price of carbon and some of the research variables. Figure 4 shows bivariate cluster maps for CO_2e emissions and GDP with price of carbon for 2021. For Sample 1, which consisted of 297 municipalities, 23.6% of the municipalities had spatial clusters between GDP and price of carbon. For Sample 2, with 111 municipalities, this percentage remained approximately 12.6%. For CO_2e emissions and the price of carbon, high-high grouping was present in 42 municipalities (Figure 4.a) and in 6 municipalities (Figure 4.c). The mesoregions of Itapetininga, Bauru and Litoral Sul Paulista stand out as this grouping indicates that municipalities with high CO_2e emissions were surrounded by municipalities with high price of carbon on average. This result is understandable because the higher the level of CO_2 emissions is, the higher the cost of pollution.

Regarding the relationship between GDP and price of carbon, we note the high-high grouping present in 26 municipalities of Figure 4.b and in 6 municipalities of Figure 4.d, which shows that municipalities with high GDP were surrounded by municipalities with high price of carbon on average. This finding was due to the greater dynamism of production in these regions. A higher GDP provides a greater structure for regional production, which may increase both CO_2 emissions and carbon values.

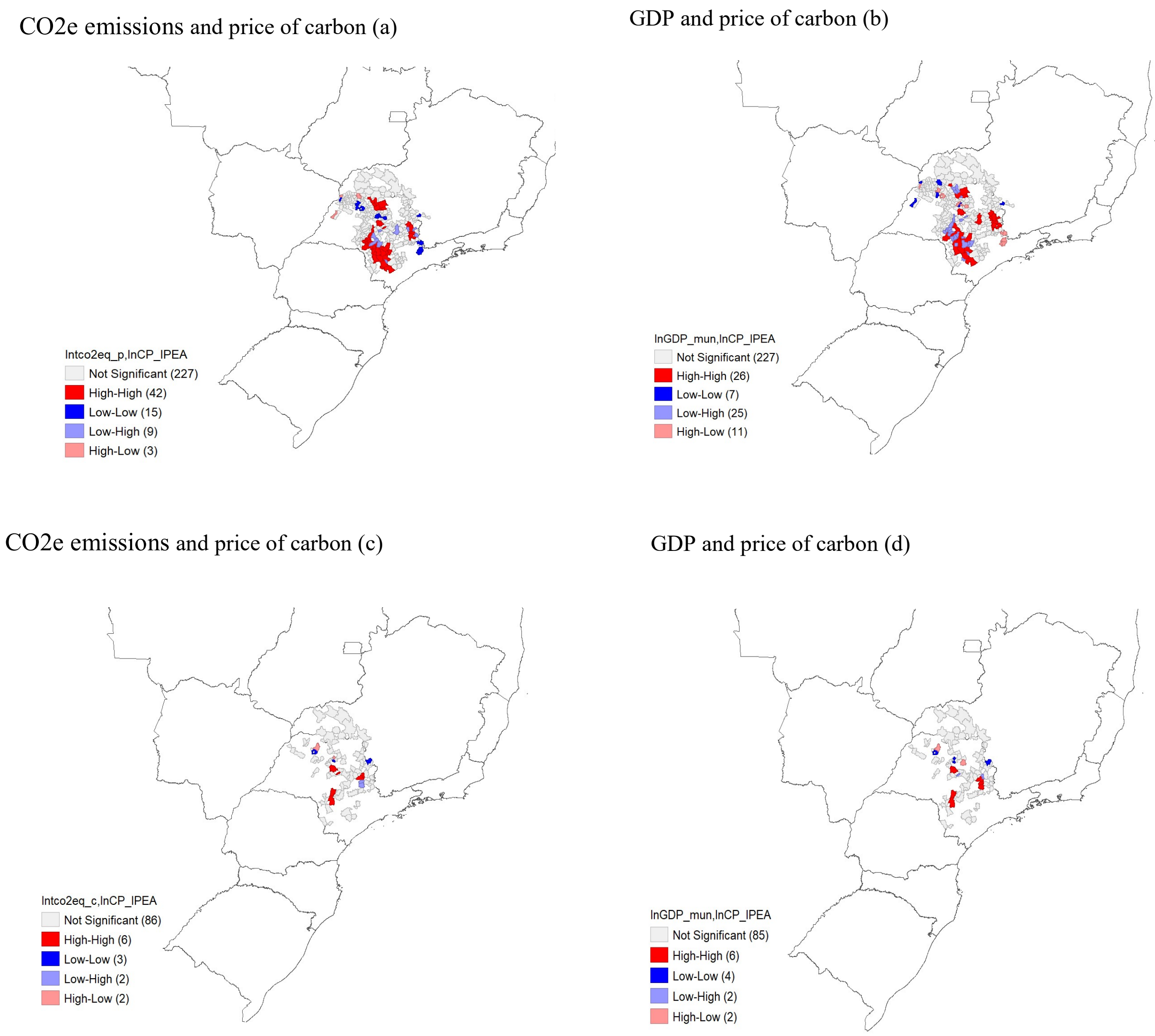


Figure 4 - Bivariate cluster maps in 2021
Source: Authors' calculations based on Gurgel and Laurenzana (2016), ANEEL (2022), IBGE (2022), IBGE (2021), IBGE (2020), SFB (2021).

Table 4 shows the pricing of carbon in citriculture in Minas Gerais and São Paulo. The first observation is related to the difference in the values between the two models: the inclusion of the 'renewable energy' variable implies lower carbon values, and in the state of Minas Gerais, the value was USD7.91 tCO_2e at 2021 prices. The adoption of cleaner production patterns effectively enables a reduction in CO_2e emissions and a reduction in associated social costs. In São Paulo, on the other hand, this inclusion resulted in higher carbon values than for Sample 1 (USD7.89/tCO_2e at 2021 prices). This finding was probably due to the characteristics of the energy supply in the state of São Paulo. The municipalities analyzed in São Paulo had a higher installed capacity of renewable energy and a higher level of CO_2e emissions from citrus cultivation. The municipalities analyzed in Minas Gerais had a lower installed capacity of renewable energy and a lower level of CO_2e emissions, which may have affected the price of carbon in these regions.

Table 4 - Estimated price of carbon in 2021

2021	Sample 1 297 municipalities			Sample 2 111 municipalities		
	MG	SP	Total	MG	SP	Total
Number of municipalities	23	274	297	15	96	111
USD/tCO_2e*	8.09	7.69	7.72	7.91	7.89	7.88

Source: Authors' calculations based on (ANEEL, 2022; Gurgel; Laurenzana, 2016; IBGE, 2020, 2021, 2022b; SFB, 2022).
* Monetary values were deflated by the Getulio Vargas Foundation's General Price Index (IGP-DI) for the year 2021.

The second conclusion from Table 4 is that the estimated values are higher than the reference prices adopted for municipalities (USD7.0/tCO_2e). These values were higher in both samples analyzed: USD 7.72/tCO_2e on average for the sample excluding renewables and USD 7.88/tCO_2e for the sample including renewables. The estimated coefficients in Table 3 suggest that these higher values expressed the structural characteristics of the citrus sector in the Brazilian regions considered. Thus, the cost of abating one unit of GHG would lead to higher price of carbon than the one used as the reference in the model.

4. Conclusions

This work aimed to price carbon in Brazilian citriculture. A series of variables, namely, municipal GDP, area, share of citriculture in agricultural GDP, CO_2 emissions per capita for the sector, environmental preservation and production of renewable energy, was developed for two municipal samples in the states of Minas Gerais and São Paulo. Using a spatial autoregressive error model (SEM), the spatial dependence between municipal GDP and price of carbon was tested. A 1% increase in the level of municipal GDP was associated with a 0.654% (Sample 1) and 0.689% (Sample 2) increase in the carbon value in citriculture. A high-high clustering was also found in 26 municipalities in Sample 1, indicating that municipalities with higher GDPs tend to have higher price of carbon.

A positive relationship between carbon emissions and the price of carbon, contrary to the literature on structured markets (Bakam; Pajot; Matthews, 2012; McKinsey & Company, 2009), indicates a failure of economic incentives to reduce emissions. This suggests that the environmental costs of carbon emissions are not being internalized by the market. The introduction of a regulated carbon market could help internalize these costs by providing incentives to reduce emissions through carbon pricing.

Despite the importance of social costs for public policies, there are no official studies on carbon pricing for citriculture in Brazil. Our study addresses this gap and contributes to the discussion on environmental asset pricing in the sector. For Brazilian citrus, there has been great demand for the valuation of carbon stocks and emissions (EMBRAPA, 2022b; Neves et al., 2011), but the price of carbon is still a much less explored topic. This study has implications for policies, as it has shown that higher share of agriculture in the GDP and increased renewable energy production may contribute to reducing the price of carbon. These findings are consistent with the literature showing that decarbonizing economies may promote social and environmental gains (Anthoff *et al.*, 2011; Raihan *et al.*, 2023).

The citrus carbon price was USD 7.88/tCO_2e including the energy variable and USD 7.72/tCO_2e excluding this variable. However, the inclusion of the energy variable resulted in a decrease in the carbon valuation in Minas Gerais, but an increase in São Paulo, which is related to the energy supply conditions of the evaluated municipalities.

A limitation of our research was the use of the CO_2e emissions coefficient in the national citrus sector for each Brazilian municipality. Due to the lack of technical coefficients for each Brazilian municipality, it is common to use indicators as proxies in the inventories currently carried out (de Azevedo *et al.*, 2018). It is also important to highlight that the carbon footprint of citrus may vary depending on the origin of the production and the delivery destination of the orange and increase as more production stages are included in the analysis. In addition, the level of greenhouse gas emissions may vary according to the type of orange used, climate and productivity of orange groves.

In markets where the supply and demand for carbon credits is incipient, such as the citrus sector in Brazil, the relationship between carbon emissions and the price of carbon may be affected by broader economic, social and environmental factors. Government policies can also play a key role in determining the price of carbon (Bakam; Pajot; Matthews, 2012; Gouvello, 2010; Gurgel; Laurenzana, 2016). Particularly in countries such as Brazil, where carbon pricing policies have not yet been implemented, the relationship between CO_2 emissions and the price of carbon is strongly influenced by the factors mentioned above. The regulation of the carbon market in Brazil through Bill 2.148/2015, with the possible inclusion of agriculture in the carbon pricing system, tends to increase the demand for carbon credits or emission reductions in the agricultural sector. This could have a positive impact on the scarcity and price of carbon credits. On the other hand, there could be incentives for farmers to adopt more sustainable agricultural practices, which could reduce carbon emissions and ultimately lower the price of carbon in the long run.

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