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Polluting Emissions and GDP: Decoupling Evidence from Brazilian States[1]

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Abstract

We provide a comprehensive analysis of the relationship between greenhouse gas (GHG) emissions and GDP in Brazil using both aggregate and state-level data. The trend or Kuznets elasticity is about 0.8 for Brazil, higher than that in advanced countries but below that of major emerging markets. The elasticity is somewhat higher for consumption-based emissions than for production-based emissions, providing evidence against the "pollution haven" hypothesis. Additional evidence comes from state-level data analysis where one can observe a great deal of heterogeneity but also some hope as far as decoupling is concerned. In addition to the trend relationship between emissions and output, we find that there does not seem to exist a cyclical relationship holding in Brazil at the aggregate level (despite having become more procyclical over time), but it does exist in a few states.

Keywords: Green House Gas, Cycle, Environmental Kuznets Curve, Brazil, Regional analysis, Detrending, Filtering

JEL Classifications: E32, O44, Q43, Q54, Q56

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1. Introduction

Energy's role in attaining socio-economic development has been historically recognized (see e.g. Mulder and de Groot, 2011; Henriques and Borowiecki, 2014). The relevance of BRICs for the environment is determined by their unique stage and pace of economic development requiring industrial-based production, which often relies on non-sustainable solutions.[3] Global carbon dioxide emissions rose nearly 50 percent over the last two decades (Peters et al., 2012). To the international community, the link between economic activity and environmental pressures represents a risk to the global efforts towards emission reductions (OECD, 2002).

Brazil ranks as the world's seventh largest economy, has a population of over 200 million and a landmass two times larger than the European Union. Brazil also plays an important and unique role in climate change: it is within the world's list of top 10 largest greenhouse gas (GHG) emitters (IEA and REN21, 2012) and home to one of the greatest ecosystems and forests of the planet. Despite the high and increasing share of renewables in its energy mix, Brazil's strong and continuous economic growth in recent decades (that ejected millions of Brazilians out of poverty and redistributed the fruits of its abundant natural resources) raises environmental concerns since both energy demand and related GHG emissions continue to grow. This suggests that Brazil needs further improvements in environmental services and more efficient implementation of environmental laws.[4] The main sources of GHG emissions are energy power, transportation and agriculture (including land use, cattle and illegal deforestation) (MCT, 2009).[5] Agriculture accounts for 25 percent of Brazil's emissions (McKinsey & Company, 2012). At the same time, the fastest emissions growth in 2012 occurred in Brazil's energy sector.[6]

That being said, Brazil still represents one of the countries with the biggest potential to curb emissions. Brazil is very eco-friendly when compared with the energy sector of most other major economies, boasting the world's most advanced bioethanol industry and producing most of its electricity from hydropower.[7] Agricultural policy in Brazil has increasingly been focused on

[3] China, India and Brazil, recognizing their importance in the global warming problematic, announced pledges on domestic emissions reduction (Richardson et al., 2009; UNFCCC, 2010).

[4] Recognizing the international call to mitigate carbon emissions, Brazil ratified the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 along with the Kyoto Protocol in 2002.

[5] High emissions from land use mostly occur in the tropical regions, where forest carbon density is highest (Baccini et al., 2012). Moreover, it is widely recognized that Land-Use Change and Forestry is a key sector of climate change (IPCC, 2007). Emissions from land use change grew 23 percent in 2016, accounting for roughly half of all GHG released into the atmosphere by Brazil. This was driven by a 29 percent increase in Amazon deforestation between 2015 and 2016, according to the National Institute for Space Research ("INPE"). Brazil suffered and still regularly suffers pressure to curb destruction of the Amazon rainforest (Cerri, 2010). Between 1970 and 2010, approximately 18 percent of the Brazilian Amazon was deforested (Baccini et al., 2012), with the primary cause being demand for new land for the cultivation of soybeans and expansion of pasture (Barona et al 2010, Hosonuma et al., 2012).

[6] Figures from the 2009 Brazilian Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases show that energy consumption-induced CO2 emissions are the second major source of GHG emissions in Brazil, after land-use change and forestry-related emissions, which grew of more than 70 percent from 1990 to 2005 (MCT, 2009).

[7] It was in the context of the stagnation surrounding the oil shocks of the 1970s that policies for energy diversification and oil substitution were implemented (Araujo and Ghirardi, 1987). Between 1975 and 1985, the inauguration of several hydropower plants and the launch of the National Alcohol Program allowed an extraordinary reshaping of the

sustainable development. In fact, the increased productivity of agricultural production has been reducing the pressure on deforestation and the biofuels production has been increasing the range of renewable sources that can be substituted to fossil fuels (OECD/FAO, 2015).[8] Reducing tropical deforestation is desirable, not only because it might be one of the cheapest options to effectively reduce global CO2 emissions (Kindermann et al., 2008), but also because it would enhance sinks and protect valuable ecosystems (Canadell and Raupach, 2008).

The strong link between economic growth and emissions in Brazil deserves more attention (see section 2 for a review). In fact, progress on global climate change goals will be difficult to achieve unless the pace of emissions slows down significantly in Brazil. Some argue that Brazil's high emissions are due in large part to its major role in the international trading system (see e.g. Machado et al., 2001); the “pollution haven” hypothesis asserts that "emissions reductions observed in developed nations are partly the result of shifting dirty production to developing nations" such as Brazil (see Kerasley and Riddel, 2010). That being said, recent shifts in domestic policy seem to indicate that Brazil's policymakers are determined to further transform the country's energy system in ways that will reduce both energy-related carbon dioxide emissions and air pollution faster than previously anticipated.[9] In September 2015, Brazil became the first major developing country to pledge an absolute reduction in GHG emissions ahead of Paris climate talks: it would cut its emissions by 37 percent by 2025 from 2005 levels by reducing deforestation and boosting the share of renewable sources in its energy mix.

In this paper, we provide evidence on the relationship between emissions and GDP growth in Brazil and investigate whether there are signs of decoupling between the two. As in Cohen et al. (2018), we distinguish the trend relationship between emissions and GDP from the cyclical relationship. The Kuznets elasticity - the response of trend emissions to trend GDP - is about 0.8 in Brazil, which is higher than that in major advanced economies but lower than in many emerging markets. The estimate is robust to alternative methods of detrending the data such as the commonly-used Hodrick-Prescott filter and the newer filter proposed by Hamilton (2017). We find that the elasticity is somewhat lower with production-based emissions than with consumption-based emissions. The direction of these results is not entirely consistent with the pollution haven hypothesis but the quantitative difference between the two elasticities is not large (or statistically different from one another). Consequently, our findings suggest that shifts in the allocation of global production across countries are not a major driver of shifts in the pattern of emissions growth in Brazil.

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national energy matrix. Developments of new renewable energy sources allowed improvements in the quality of Brazilian’s energy matrix and converted it into the cleanest among transition economies (Gouvello, 2010).

[8] Nowadays agriculture in Brazil supplies almost half of the total energy supply. Renewable energy from agriculture comprises mainly of sugarcane biomass (42 percent) and hydraulic energy (28 percent).

[9] Government policy to reduce emissions has been largely focused on reducing emissions from deforestation through the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAM) introduced in 2004. Following this success, on December 29, 2009 Brazil adopted Law 12.187, which established the country’s “Política Nacional sobre Mudança do Clima” (PNMC), Brazil’s National Climate Change Policy.

Then, our analysis for 27 states does not reveal any underlying inverted U-shape relationship between the intensity of emissions-GDP relationship and the level of per capita GDP (or evidence of the EKC - Grossman and Krueger, 1995). That is, at the state level, we do not observe that Kuznets elasticity initially increases with provincial per capita real GDP but then declines. However, results from state-level data hold out the hope since several individual states show signs of decoupling and the relationship between emissions and GDP growth is expected to weaken as Brazil gets richer.

We also provide evidence on the cyclical relationship between emissions and GDP growth. The cyclical elasticity - the response of the cyclical component of emissions to the cyclical component of GDP - ranges from -0.1 to 1.5, depending on the filtering method used and on whether production-based or consumption-based emissions are used. That being said, results seem to suggest short-run acyclicality between emissions and growth, which has become slightly more procyclical as time went by. Finally, we further find evidence of asymmetry in the cyclical relationship: the elasticity is higher in booms than during busts, and thus Brazil's emissions go up more when GDP is above trend than they decrease when GDP is below trend. However, this result seems to be mainly driven by a few states. To our knowledge, this is the first study to provide a comprehensive look at the extent of decoupling of emissions and output for Brazil, looking at both trends and cycles, using both production-based and consumption-based estimates, and using both national and sub-national data. In addition, we also employ recent filtering techniques to detrend time series of interest and rely on sophisticated approaches to estimate time-varying coefficients. Some other studies looked at long-run growth rates of emissions and GDP for a large group of countries. For instance, Csereklyei and Stern (2015) used long-run growth rates for 93 countries and found weak decoupling, while Jakob et al. (2012) found that the average developing economy experienced above-average growth of total carbon dioxide emissions over the 1971-2005 period.

The remainder of the paper is organized as follows. Section 2 briefly presents the literature on the broad topic of emissions and economic activity in Brazil. Section 3 discusses the paper's empirical approach, aggregate level data, and the baseline estimates of the cyclical and Kuznets elasticities across a broad range of filtering techniques and data. Section 4 broadens the analysis by looking to trends and cycles at the state level. In the last section, we conclude and the policy implications are discussed.

2. Literature Review

Most of the literature relating energy pollution and economic activity has focused on the empirical analysis of the trend behavior between emissions and GDP, i.e., has focused on the long-run (the Kuznets elasticity) and omitted the short-run cyclical relationship that might equally exist. However, the amount of research inspecting the so-called Environmental Kuznets Curve (EKC) in the BRICS countries is limited. Some contributions are due to Tamazian et al. (2009) who study the growth-pollution nexus in the BRIC countries to follow up on the criticism of the EKC hypothesis provided by Stern (2004). They found that at higher levels of economic growth, carbon dioxide emissions decrease with economic growth, therefore confirming the existence of an inverted U-shaped relationship. The application of EKC in the BRICS is also studied by Chakravarty and Mandal (2016) by means of panel data techniques. The authors found mixing evidence depending on the exact technique used.

Other studies empirically assessing the link between emissions and GDP growth in the BRIC countries include the works by Pao and Tsai (2010) who examined dynamic causal relationships between pollutant emissions, energy consumption and output for a panel of BRIC countries over the period 1971-2005. Wendy et al. (2014) focused on the nexus between electricity consumption, growth and emissions in the same group of countries. Melike and Tashin (2014) looked at coal and natural gas instead and their relationship with economic activity also in BRICs. Wu et al. (2015) reexamined the relationship between energy consumption, urban population, economic growth and carbon dioxide emissions in the BRIC countries between 2004-2010 using a novel multi-variable grey model.

Studies specifically directed to the Brazilian case include the study by Machado and Schaeffer (2005) who found that a significant part of the upward trend in overall energy intensity in Brazil was related to both economic restructuring toward low value-added and energy-intensive activities. Wachmann et al. (2009) examined the sources of changes in energy use of the Brazilian economy of industries and households from 1970 to 1996, using structural decomposition analysis based on the logarithmic mean divisia index technique. Pao and Tsai (2011) examined the dynamic relationships between pollutant emissions, energy consumption and output in Brazil for the period 1980-2007. They used a grey model to predict the carbon dioxide emissions in Brazil. Also, Freitas and Kaneko (2011a) examined the occurrence of a decoupling between the growth rates in economic activity and carbon dioxide emissions from energy consumption in Brazil from 2004 to 2009. The decoupling was highlighted when economic activity and carbon dioxide emissions moved in opposite directions in 2009. In another paper, Freitas and Kaneko's (2011b (EP)) study evaluated the changes in carbon dioxide emissions from energy consumption in Brazil for the period 1970–2009. They decomposed emissions into production and consumption activities allowing computing the full set of energy sources consumed in the country. Most of the existing decomposition studies addressing the issue of emissions from energy consumption in Brazil and the main factors affecting changes in carbon dioxide emissions, identify economic activity and population pressure as main factors driving emissions growth. Likewise, energy mix factor is pointed as the main factor contributing to emission mitigation (Mendonca and Gutierez, 2000; Medeiros and Dezidera, 2006; Kojima and Bacon, 2009).

Because of the relevance and peculiarities of Brazil's energy composition and emission pattern within the context of climate change, the country has also been subject to several comparative studies. For example, Luukkanen and Kaivooja (2002) identified that, compared with several other nations, the trend in carbon intensity in Brazil was associated with changes in the fuel composition. In other words, the authors found that reduction of carbon intensity of energy consumption reflected the diversification of Brazilian energy mix towards clean sources. Bacon and Bhattacharya (2007) pointed out that energy intensity in Brazil was a contributing factor towards higher emissions standards, while the observed performance of countries like Russia, India and

China suggested that improvements in energy intensity had been the main factors for emissions reduction. Kojima and Bacon (2009) observed that the exceptional performance of energy mix in Brazil goes against the general decline in the weight of energy mix worldwide.

All in all, the literature does not seem to provide a systematic analysis of Brazilian's emissions-growth nexus at both aggregate and sub-national level using the variety of concepts (trend vs cycle) and techniques employed here. Hence, this paper aims to fill such gap.

3. Trends and Cycles at the Aggregate Level

3.1 Empirical Approach

To understand empirically the relationship between emissions and real GDP, we first consider the following specification:

$$\Delta e_t = \alpha + \omega \Delta y_t + u_t \tag{1}$$

where Δe_t and Δy_t are the growth rates of emissions and real GDP, respectively. We then depart from this specification to distinguish cycles from trends and thereby to shed light on the recent decoupling phenomena seen in several advanced economies. As in Cohen et al. (2018), we refer to the relationship between detrended real GDP and emissions as the Environmental Okun's Law:

$$e^c{}_t = \beta^{okun} y^c{}_t + \varepsilon^c{}_t \tag{2}$$

where $e^c{}_t$ and $y^c{}_t$ are the cyclical components of the log of emissions and log of real output, respectively, and β^{okun} is the cyclical elasticity. We also consider the long-term relationship between emissions and real GDP by analyzing their respective trends. The Kuznets estimate, $\beta^{kuznets}$, relates trend real GDP, $y^\tau{}_t$, with trend emissions, $e^\tau{}_t$, such that:

$$e^\tau{}_t = \gamma + \beta^{kuznets} y^\tau{}_t + \varepsilon^\tau{}_t \tag{3}$$

We estimate these equations for both national and state-level data. The model is estimated with a constant term (γ), translating the fact that states are expected to be endowed with relatively different initial conditions and, therefore, with some inherent historical level of emissions.

To extract the cyclical and trend components for a generic variable x_t (denoted $x^c{}_t$ and $x^\tau{}_t$, respectively) where $x_t = \{y_t, e_t\}$, we employ the commonly used Hodrick-Prescott (HP, 1981, 1997) filter. This filter minimizes the following function:

$$\min_{\tau_t} \left\{ \sum_{t=1}^{T} (x_t - x^\tau{}_t)^2 + \lambda \sum_{t=1}^{T} [(x^\tau{}_t - x^\tau{}_{t-1}) - (x^\tau{}_{t-1} - x^\tau{}_{t-2})]^2 \right\} \tag{4}$$

where λ is the smoothing parameter set at 100, as common practice when employing annual data. The greater the value of λ, the larger is the penalty on variations of the trend's growth rate (i.e., the sum of the squares of the trend's second differences). The criticisms surrounding the use of the HP filter, in particular in the context of a large sample of very heterogeneous countries, are well-known (see Harvey and Jaeger, 1993; Cogley and Nason, 1995; Hamilton, 2017). We therefore also compare the cyclical and trend series with the ones proposed by Hamilton (2017) as an alternative filtering method. For that purpose, we estimate:

$$x_{t+h} = \gamma_0 + \sum_{j=0}^{k} \gamma_j + x_{t-j} + u_{t+h} \tag{5}$$

where $x_t = x^{\tau}{}_t + x^{c}{}_t$. The non-stationary part of the regression provides the cyclical component:

$$x^{c}{}_t = \hat{u}_t \tag{6}$$

while the trend is given by

$$x^{\tau}{}_t = \hat{\gamma}_0 + \sum_{j=0}^{k} \hat{\gamma}_j + x_{t-h-j} \tag{7}$$

Hamilton (2017) suggests that h and k should be chosen such that the residuals from equation (5) are stationary and points out that, for a broad array of processes, the fourth differences of a series are indeed stationary. We choose h = 2 and k = 3, which is line with the dynamics seen in both emissions and GDP. We also use the Baxter-King (BK) and Christiano-Fitzgerald (CF) band-pass filters. BK derives a finite approximation to the infinite-order symmetric moving-average filter by estimating the cyclical component of a time series as:

$$x^{c}{}_t = \sum_{j=-k}^{k} \hat{\gamma}_j x_{t-j} \tag{8}$$

where $\hat{\gamma}_j$ are the modified weights for a finite-order symmetric moving-average filter such that $\sum_{j=-k}^{k} \hat{\gamma}_j = 0,\ \hat{\gamma}_j = \gamma_j - \bar{\gamma}_k$ and $\hat{\gamma}_j = \gamma_{-j}$ with γ_j being the ideal weight in the time domain and $\bar{\gamma}_k$, its mean truncated at $\pm k$. Removing the cyclical component of the time series x_t provides the trend component $x^{\tau}{}_t$. Similarly, CF derives a finite approximation to the ideal band-pass filter by minimizing the mean squared error between the filtered series and the series filtered by an ideal band-pass filter, with the cyclical component given by:

$$x^{c}{}_t = \gamma_0 x_t + \sum_{j=1}^{T-t-1} \gamma_j x_{t+j} + \bar{\gamma}_{T-t} x_T + \sum_{j=1}^{t-2} \gamma_j x_{t-j} + \bar{\gamma}_{t-1} x_1 \tag{9}$$

where $\gamma_0, \gamma_1, ...$ are the weights used by the ideal band-pass filter and $\bar{\gamma}_{T-t}$ and $\bar{\gamma}_{t-1}$ are linear functions of the ideal weights. Equations (1), (2), and (3) are estimated using ordinary least squares (OLS) for the aggregate data for Brazil as a whole and for each state.

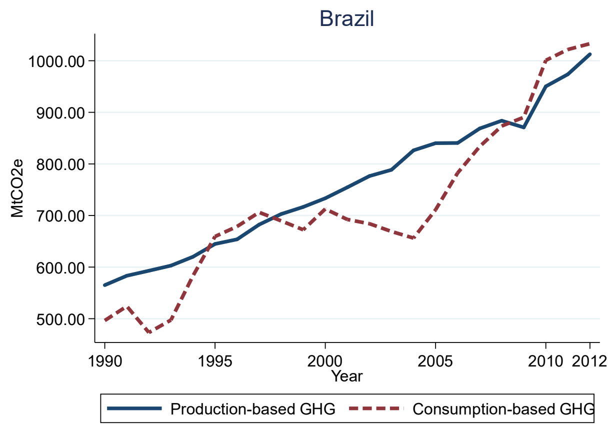
3.2 Data

Real GDP (in national currency) and real GDP growth used for the baseline exercise for Brazil at the aggregate level are taken from the latest update of the IMFs World Economic Outlook (WEO) database. Our baseline analysis covers the period 1990-2012 and focuses on both CO2 emissions as well as GHG emissions. GHG emissions are aggregated by the World Resources Institute by types of atmospheric gases (including CO2 and non-CO2 emissions, such as methane (CH4), nitrous oxide (N2O), and fluorinated gases (F-gas)) according to their 100-year Global Warming Potential as per the IPCC's 2nd Assessment Report. CO2 emissions are taken from the International Energy Agency and are derived from fossil fuel combustion and cement manufacture. CH4 and N2O are taken from both the U.S. Environmental Protection Agency (US-EPA) for industrial processes and waste, and from the Food and Agriculture Organization (FAO) for agricultural emissions. F-gas emissions are provided by the US-EPA and fall within the industrial processes sector. CO2 emissions account for the vast majority of emissions (more than 83 percent of total emissions), followed by methane at around 9 percent.

In addition to these production-based emissions, we use consumption-based emissions that include the net emissions embodied in international trade. For CO2 consumption based emissions we rely on the Eora multi-region input-output (MRIO) database. [10] In order to get the approximate equivalent consumption-based estimates for GHG, we take an arguably simplistic shortcut: that is, we use the difference between CO2's consumption- and production-based emissions from Eora's to adjust our GHG production-based estimate. Figure 1 shows both production- and consumption-based GHG emissions for our baseline sample period (1990-2012). Brazil, as is the case for several other emerging and low-income economies, has generally lower levels of emissions when net emissions from international trade are included than when only production-based emissions are accounted for.

[10] Additional details about the database can be found in Lenzen et al. (2012, 2013).

Figure 1. Consumption- and Production-Based GHG Emissions in Brazil

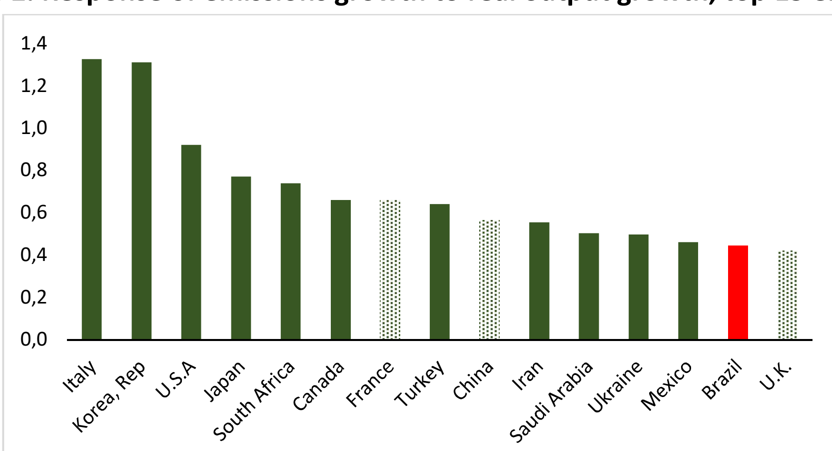


Source: author calculations.

3.3 Baseline Results

A first crack at the data on emissions and real GDP at the aggregate level yields little evidence of decoupling in Brazil. Figure 2 presents the results of regressions, estimated over the period 1990 to 2014, of growth in greenhouse gas (GHG) emissions on the growth of real GDP for the 15 largest emitters (cf. equation 1 above). The bars in the figure show the estimated emissions-output elasticity, the percent change in emissions for a 1 percent change in output, for each of the 15 countries. The elasticity is positive for all countries, with an average of 0.7, with Brazil obtaining a coefficient of 0.5.

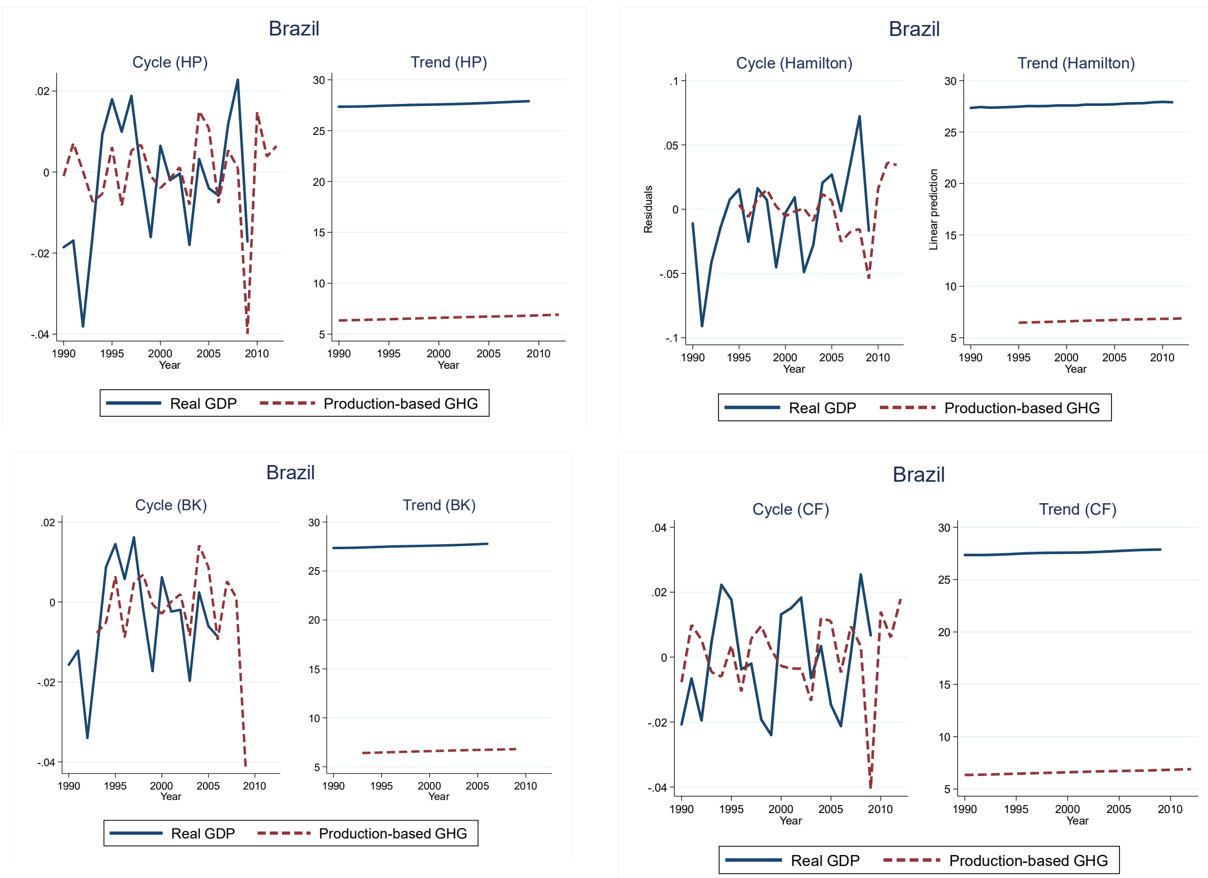
Figure 2. Response of emissions growth to real output growth, top 15 emitters



Note: Each bar denotes the response of emissions growth to output growth. Dark shaded green (red for Brazil) denote statistically significant coefficient estimates at the 10 percent level or better, while light shaded green bars denote statistically insignificant coefficient estimates.
Source: author calculations.

The remainder of this section provides a thorough robustness analysis of alternative filtering methods used to extract the cyclical fluctuations from their trend components, contrasting the cyclical and Kuznets elasticities derived from these filters. Figure 3 shows the cycles and trends extracted from the different filters for Brazil's real GDP and production-based emissions. Despite the divergent peaks and troughs at the cyclical level, all filters depict trend real GDP to be parallel to trend emissions. There is thus no sign yet of a clear decoupling between emissions and growth at the aggregate level.[11]

Figure 3. Trends and Cycles in Emissions and Output—Brazil, 1990-2012



Note: "HP" denotes Hodrick-Prescott filter; "Hamilton" denotes the Hamilton (2017) filter; "BK" denotes the Baxter-King filter; finally, "CF" denotes the Christiano-Fitzgerald filter.
Source: author calculations.

Table 1 presents the cyclical and Kuznets coefficients across the different filtering methods. Although several advanced economies have experienced a decoupling between trend real GDP and trend production-based emissions over the same sample period (Cohen et al., 2018), Brazil presents a positive and statistically significant environmental Kuznets elasticity of 0.88. The

[11] A variance decomposition of emissions across the different filters shows that most of the variance in emissions is captured by the variance in trend emissions, with the relative contribution of the variance of the cyclical terms and the covariance between the trend and cyclical series being negligible.

alternative filtering methods used to estimate equation (3) point to a similar average coefficient, ranging from 0.85 to 0.97 with the Hamilton and BK filter, respectively. This suggests Brazil is yet to transition to a low carbon path.[12] The cyclical coefficient obtained from equation (2) suggests that emissions tend to be generally acyclical (while positive, the coefficient is not precisely estimated, ranging between -0.12 to 0.24). Using alternative measures of emissions confirms our baseline results as shown in the bottom part of Table 1.[13] The Kuznets elasticity derived from using CO2 emissions is larger than when methane and other greenhouse gases are included (1.22), which suggests that when trend GDP grows, trend CO2 emissions grow faster than other damaging gases. Despite Brazil being one of the main exporters of carbon-intensive inputs, its consumption-based Kuznets coefficient shows that trend consumption-based emissions grow at a similar rate as its production-based emissions.

Table 1. Contrasting Elasticities at the Aggregate Level, 1990-2012

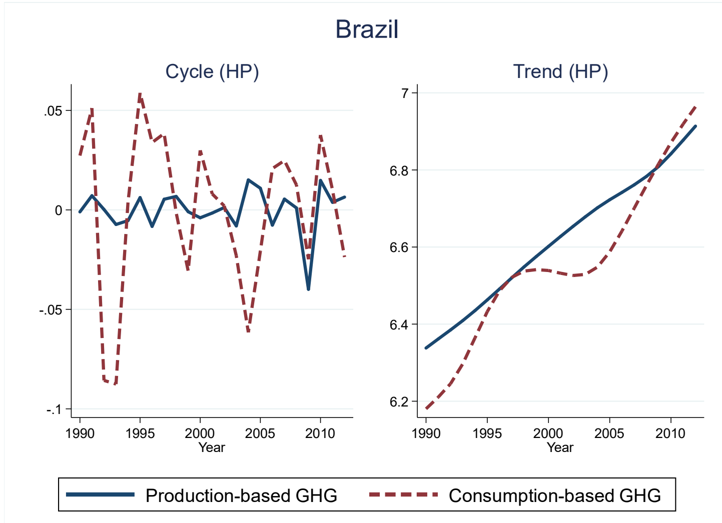
Brazil	$\hat{\beta}^{Okun}$	$\hat{\beta}^{Kuznets}$
Growth rates, production based GHG	0.241	-
Growth rates, production based CO2	0.945**	-
Alternative Filtering Methods		
HP filter, production based GHG	0.215	0.881***
Hamilton filter, production based GHG	0.015	0.849***
BK filter, production based GHG	0.236	0.975***
CF filter, production based GHG	-0.120	0.865***
Alternative Emissions Data		
Production based CO2	0.954***	1.216***
Production based GHG with LULUCF	-0.066	0.193**
Consumption based GHG	1.504***	0.972***

Note: *, **, ***denote statistical significance at the 10, 5, and 1 percent levels, respectively.
Source: author calculations.

Figure 4 compares the cyclical and trend components of production- vs. consumption-based emissions, with these two types of emissions displaying some co-movement, particularly in more recent years.

[12] Analyzing the Kuznets residuals confirms that these are stationary, with the Augmented Dickey-Fuller test showing that we reject the hypothesis that residuals have a unit root (results available upon request).
[13] The HP filter was used to extract the cyclical and trend components of these time series.

Figure 4. Comparison of Trends and Cycles in Production-Based and Consumption-Based Emissions, 1990-2012



Source: author calculations.

4. EKC Investigation

4.1 Trends and Cycles: Time-Varying Elasticities and The Role of the business cycle

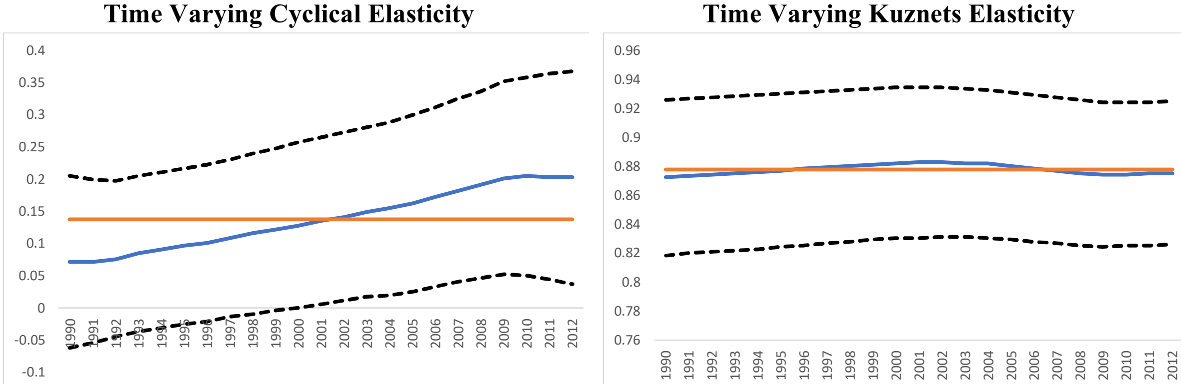
Although Brazil is one of the world's top GHG emitter, its economy is transitioning from the manufacturing of industrial goods and the extraction of carbon-intensive goods to services and more high-end goods. As Brazil gets richer - its real income per capita went from about US$8339 in 1980 to about US$11322 in 2015 (constant 2010 US$ - World Bank data) - one would expect its emissions-output elasticity to decrease over time. The previous section looked at our baseline case covering the 1990-2012 period, whereas this section explores whether time dynamics has played a role and whether it can shed light on Brazil's transition to a low-carbon path, that is, whether there are signs of a decoupling between emissions and output.

We generalize equations (2) and (3) by introducing the assumption that the regression coefficients may vary over time. In particular, the coefficients γ, β^{okun} and $\beta^{kuznets}$ are assumed to change slowly and unsystematically over time its conditional expected value to be equal to its past value. The change of the coefficients β^{okun} or $\beta^{kuznets}$ is denoted by $v_{i,t}$, which is assumed to be normally distributed with expectation zero and variance σ_i^2. In order to estimate time-varying estimates of the key parameters of interest, we rely on the Varying-Coefficient model proposed by Schlicht (1985). In this approach the variances σ_i^2 are calculated by a method-of-moments estimator that coincides with the maximum-likelihood estimator for large samples (see Schlicht, 1985; Schlicht, 2003; Schlicht and Ludsteck, 2006 for more details).[14] As discussed by Aghion and Marinescu (2008), this method has several advantages compared to other methods to compute time-varying coefficients such as rolling windows and Gaussian methods. First, it allows using all observations in the sample to estimate the degree of responsiveness of emissions to GDP in each year—which by construction is not possible in the rolling windows approach. Second, changes in the degree of responsiveness of emissions to GDP in a given year come from innovations in the same year, rather than from shocks occurring in neighboring years. Third, it reflects the fact that changes in policy are slows and depends on the immediate past.

Figure 5 shows the results of our cyclical and Kuznets time-varying elasticities between 1990-2012 for Brazil. The cyclical elasticities seem to have changed over time from a value close to zero to one close to 0.2 (which is statistically significantly different from zero – check the confidence bands). this suggests that emissions have become more procyclical over time. In contrast, the relatively high (0.88) Kuznets elasticity has been relatively stable throughout the period under scrutiny.

Figure 5: Time Varying Trends and Cycles in Production-Based Emissions, 1990-2012

Time Varying Cyclical Elasticity **Time Varying Kuznets Elasticity**



Note: the blue line denotes the time varying coefficient estimates. The orange line denotes the static (time-invariant) average estimate. The dotted black lines correspond to a +1 and -1 standard deviation confidence bands.
Source: author calculations.

We also contrast the effect of output on emissions in periods of boom versus bust by estimating:

$$e^{c}{}_{t} = \beta^{okun,boom} y_t^{c,boom} + \beta^{okun,bust} y_t^{c,bust} + \varepsilon^{c}{}_{t} \qquad (10)$$

where $y_t^{c,boom}$ is y_t^{c} from equation (2) when cyclical GDP is above trend (i.e. positive) and 0 otherwise, and $y_t^{c,bust}$ is given by y_t^{c} when it is below trend (i.e. negative) and 0 otherwise. Table

[14] The approach proposed by Schlicht (2003) is very similar to that used by Aghion and Marinescu 2008. The main difference is in the computation of the variances σ_i^2. Aghion and Marinescu (2008) uses the Markov Chain Monte Carlo (MCMC) method to approximate these variances, while Schlicht (2003) uses a method-of-moments estimator.

2 shows these estimates. Brazil's emissions-output elasticity is greater during expansionary phases of the business cycle than it is during contractions - stronger and statistically significant for the 1990-2012 period for CO2 and consumption-based GHG. This result is in contrast with Sheldon's (2017) results for the US (and several advanced economies), which show that emissions tend to fall more during recessions than they increase during booms.

Table 2. Elasticities at the Brazilian Aggregate Level during Booms and Busts

Coefficient/Period	Boom prod-GHG 1990-2012	Boom CO2 1990-2012	Boom cons-GHG 1990-2012	Bust prod-GHG 1990-2012	Bust CO2 1990-2012	Bust cons-GHG 1990-2012
$\hat{\beta}^{Okun}$	0.201	1.002***	2.441*	0.224	0.839***	0.843

Note: "prod-" denote production-based; "cons-" denote consumption-based. *, **, ***denote statistical significance at the 10, 5, and 1 percent levels, respectively.
Source: author calculations.

4.2 Trends and Cycles: A State Level Perspective

Brazil is a large economy and looking at the country as whole may reveal little information about the extent of the decoupling between emissions and GDP, since it may obfuscate important trends and cycles at the state level. States have changed enormously over the last two decades. The regional analysis that follows covers 27 states over the 1995-2013 period.[15] A similar analysis was done for other countries, such as China's provinces (see e.g. Du et al., 2012). Emissions' data come from the Climate Observatory ("Observatorio do Clima") while state-level GDP are retrieved from the Brazilian Institute of Geography and Statistics ("IBGE") until 2009 and from Brazil Central Bank from 2010.

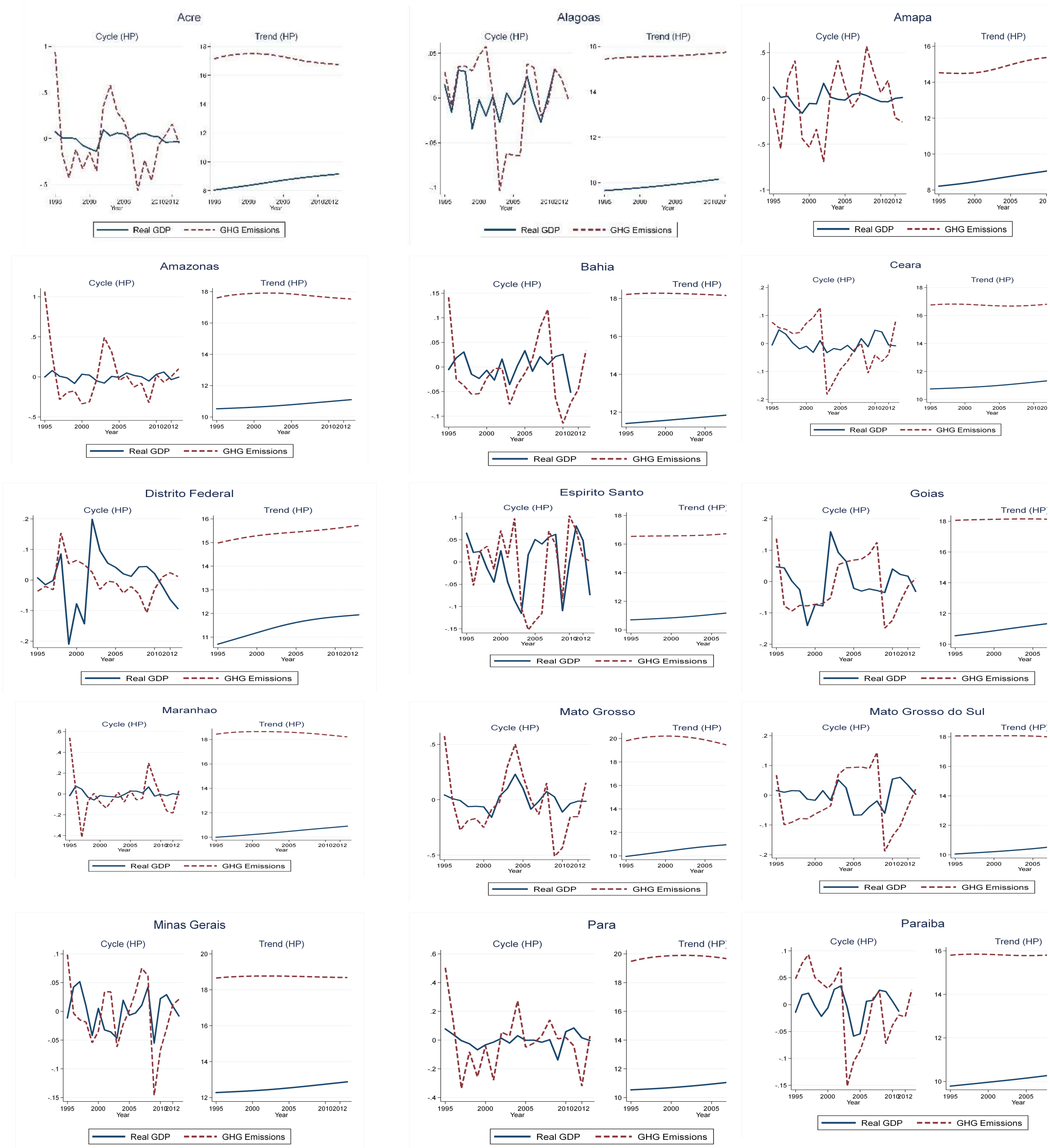
At the state level, 19 states have climate change laws, and at least seven include provisions for the creation of markets for carbon credits (Point Carbon, 2012). In 2009, Sao Paulo was the first and only state to determine its own emission reduction target of a 20 percent reduction in emissions relative to 2005 levels by 2020. The city and state of Rio de Janeiro have also pledged to reduce emissions through sub-national climate change laws. In 2010, the state of Rio passed its Policy on Global Climate Change and Sustainable Development (PEMC), a policy that sets emissions reduction targets and adaptation goals through 2030 (Institute of Applied Economic Research, 2011).

Figure 6 displays the trend and cyclical components of real GDP and CO2 emissions, extracted using the HP filter, of the states in Brazil. As in the case of the aggregate analysis, trend emissions and GDP are generally parallel, suggesting similar co-movement and, hence, little evidence of decoupling. However, across the business cycle, the synchronization between emissions and output is not visible for most states. The variance decomposition of each states' emissions show

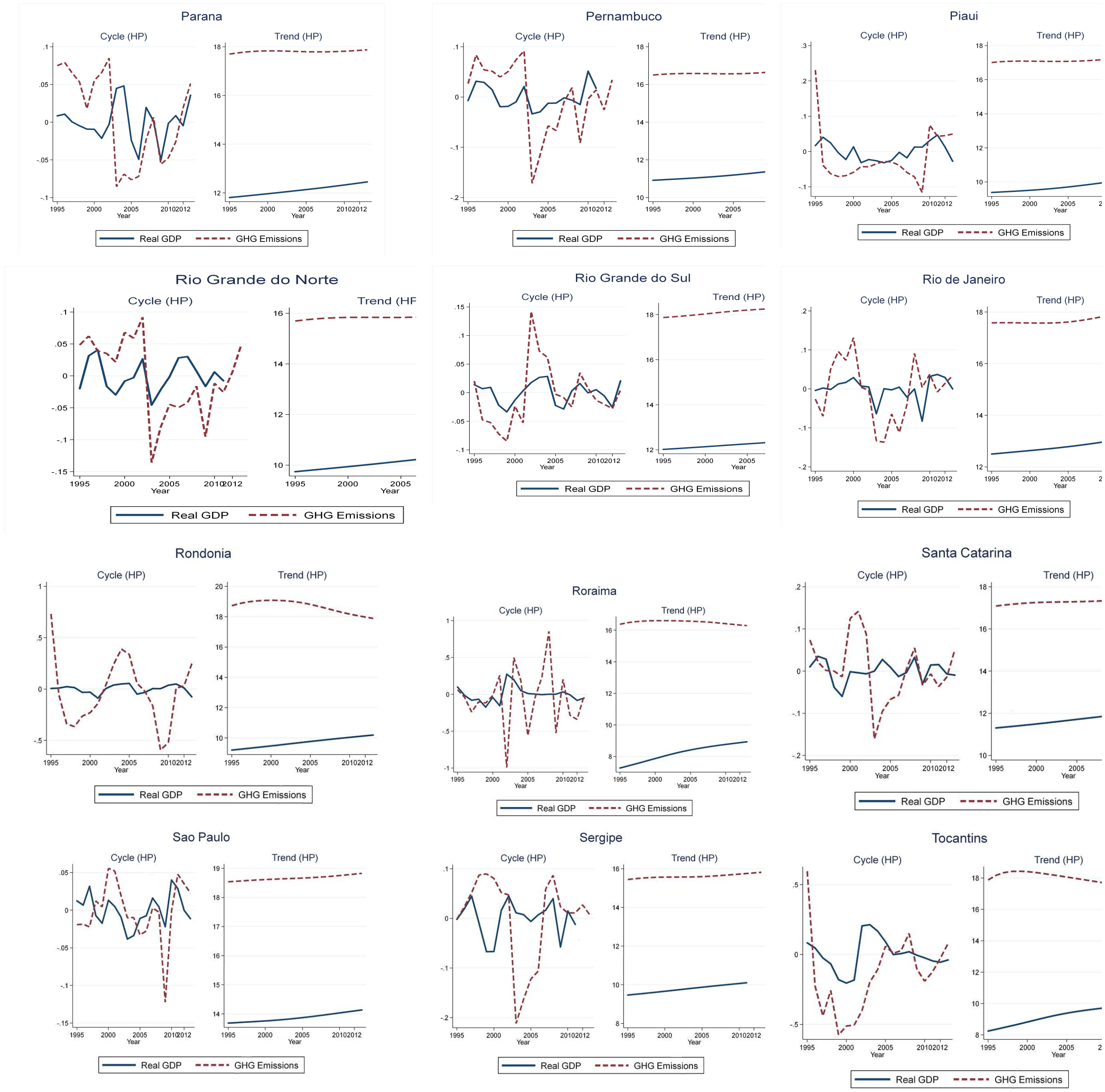
[15] The states are: Acre, Alagoas, Amazonas, Amapa, Bahia, Ceara, Distrito Federal, Espirito Santo, Goias, Maranhao, Minas Gerais, Mato Grosso do Sul, Mato Grosso, Para, Paraiba, Pernambuco, Piaui, Parana, Rio de Janeiro, Rio Grande do Note, Rondonia, Roraima, Rio Grande do Sul, Santa Catarina, Sergipe, Sao Paulo, Tocantins.

that, with the exception of the BK filter, most of the variance in emissions is captured by the variance in trend emissions.[16]

Figure 6. Trends and Cycles by Brazilian State



[16] The residuals from equation (3) for each state across the four different filters is available upon request. It shows that the Kuznets residuals are overall stationary and, thus, the Kuznets elasticities do not reflect a spurious relationship between trend emissions and trend output.



Source: author calculations.

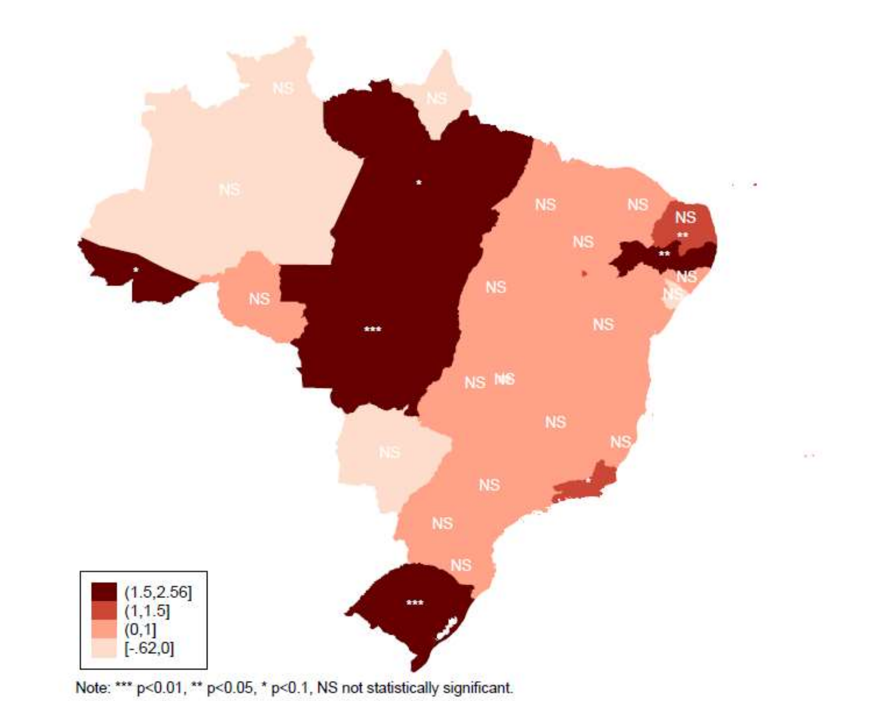
Table 3 as well as Figures 6 and 7 provide additional insights. The mean Kuznets coefficient across all states is close to 0.1, which can be seen as potentially good news for the long-run decoupling objective. An increase in GDP in the states Alagoas, Distrito Federal, Espirito Santo, Parana, Pernambuco, Piaui, Rio Grande do Norte, Rio de Janeiro, Santa Catarina, Sao Paulo e Sergipe is associated with a lower increase in emissions than in states like Amapa and Rio Grande do Sul, where trend emissions tend to grow at a faster rate than GDP. This result is robust to alternative filters; these states tend to have the largest Kuznets elasticities across the different filtering methods. On the other hand, hope exists in several states where the obtained Kuznets elasticities are negative and statistically significant, namely in: Amazonas, Bahia, Maranhao, Mato Grosso, Mato Grosso do Sul, Para, Rondonia and Tocantins. Although the elasticities derived from the changes version of the model (equation (1)) tend to be less precisely estimated – most coefficients are statistically insignificant - they are generally closer to their cyclical elasticities counterparts rather than their respective Kuznets elasticities. In addition, over the business cycle, several states have emissions growing faster than GDP in boom periods (Maranhao, Mato Grosso and Rio Grande do Sul have statistically significant cyclical coefficients above 2). While aggregate emissions tended to increase more in booms than in recessions, this is only the case for a few states, which seem to be driving the overall country-level result. States such as Bahia, Minas Gerais, Pernambuco, Roraima and Tocantins see their emissions decrease more in recessions than they would increase during periods of high growth (above trend). Finally, the maps represented by Figures 7 and 8, visually plot each state's information.

Table 3. Cyclical and Kuznets Elasticities at the State Level

Brazilian States	ω	β_{hp}^{Okun}	$\beta_{hp}^{Kuznets}$	β_{ham}^{Okun}	$\beta_{ham}^{Kuznets}$	bust	boom
Acre	2.293*	2.552*	-0.581***	1.711	-0.516	2.028	1.347
Alagoas	0.825**	0.791	0.469***	1.050	0.278***	0.259	1.349
Amapa	-0.954	-0.526	1.144***	-1.107	1.219***	2.226	-2.577
Amazonas	-0.558	-0.207	-0.419***	-0.163	-0.022	-0.252	-0.074
Bahia	-0.138	0.385	-0.293***	0.075	-0.288***	1.745*	-1.515
Ceara	1.212*	-0.131	-0.033	-0.532	-0.021	1.762	-0.023
Distrito Federal	0.144	0.214	0.509***	-0.197	0.418***	-0.391*	0.154
Espirito Santo	0.573*	0.200	0.626***	0.461	0.561***	0.315	-0.010
Goias	0.001	0.053	-0.037	-0.306	-0.177**	0.647	-0.307
Maranhao	-0.773	2.115***	-0.319***	1.875	-0.191**	-3.182	2.791*
Mato Grosso	1.231*	-0.619	-1.028***	1.285	-1.597***	1.141	2.407**
Mato Grosso do Sul	0.479	0.503	-0.349***	-0.321	-0.449***	0.393	-1.621
Minas Gerais	0.678*	1.528*	-0.053	0.957*	-0.057	1.692**	-0.940
Para	0.928	1.333**	-0.722***	0.250	-0.718**	0.591	1.120
Paraiba	0.938	0.087	0.020	0.561	0.063	1.590	1.183
Parana	0.064	1.837**	0.118***	-0.074	0.001	1.394	-1.595
Pernambuco	1.926***	0.762	0.241***	1.224	0.097	3.430**	0.769
Piaui	0.314	1.037*	0.294***	0.847	0.437***	0.453	0.437
Rio Grande do Norte	1.522***	1.773***	0.266***	1.295	0.051	1.849	0.456
Rio Grande do Sul	1.107*	1.005*	1.110***	0.611	0.769***	1.331	2.371*
Rio de Janeiro	0.834*	0.762	0.727***	0.148	0.596**	0.793	1.620
Rondonia	0.507	-0.575	-1.096***	2.365	-1.147**	-0.572	2.831
Roraima	-1.673	0.264	-0.076*	-0.614	-0.042	3.556**	-3.442**
Santa Catarina	0.757	0.026	0.360***	0.671	-0.045	0.343	-0.637
Sao Paulo	0.996**	0.585	0.571***	0.398	0.293***	1.233	0.159
Sergipe	0.325	-0.362	0.380***	0.162	0.147	-1.726	1.591
Tocantins	0.337	0.962	-0.443***	0.408	-0.133	3.922**	-1.412

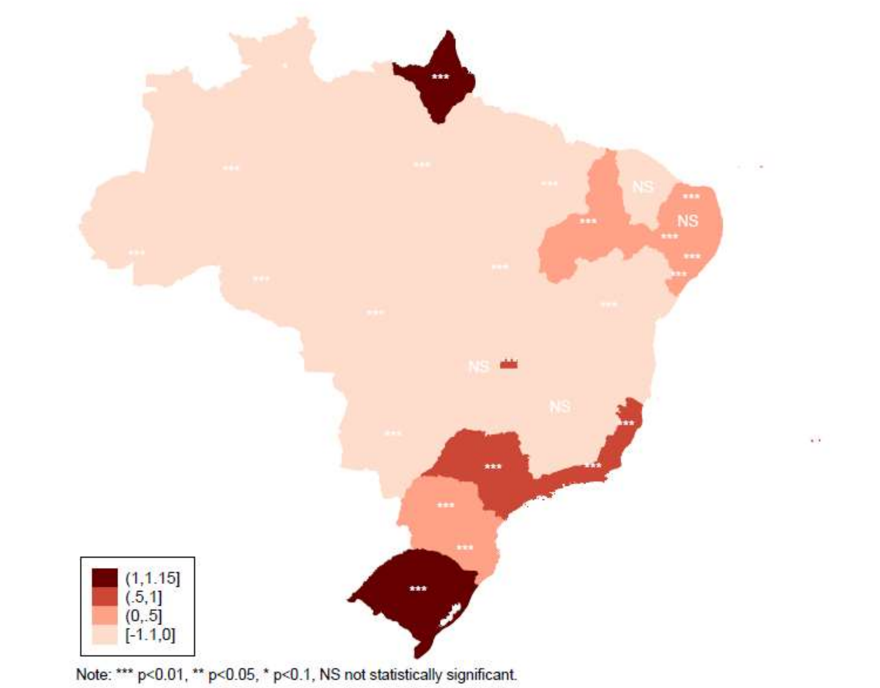
Note: ***, **, * denote statistical significance at the 1, 5 and 10 percent levels, respectively. Columns 2 and 3 are from the HP-filtered data. Columns 4 and 5 are from the Hamilton-filtered data.
Source: author calculations.

Figure 7. Cyclical Elasticities across Brazilian States



Source: author calculations.

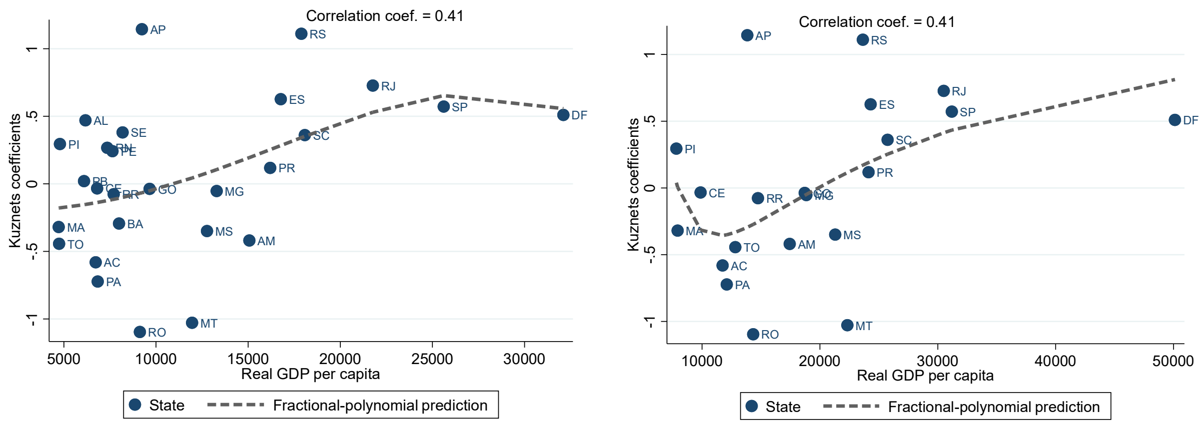
Figure 8. Kuznets Elasticities across Brazilian States



Source: author calculations.

Finally, the original EKC hypothesis suggested by Grossman and Krueger (1995), which relates the level of environmental degradation with per capita income, serves as a background for Figure 9. The figure relates the elasticities derived from the trend relationship between emissions and GDP with real income per capita in 1995(left panel) and in 2013 (right panel). Neither in earlier nor in more recent years, the fractional-polynomial prediction shows any evidence of a Kuznets behavior. That is, in Brazilian states we cannot unequivocally say that there exists an inverted U-shaped relationship or that richer states show higher signs of decoupling vis-à-vis poorer ones.

Figure 9. Kuznets Elasticities and Real GDP Per Capita across Brazilian States



Source: author calculations.

5. Conclusion and Policy Implications

This paper assessed the extent of the decoupling between emissions and real GDP for Brazil and its states by decomposing both series into their trend and cyclical components. Focusing on the trend relationship, we see little evidence of a decoupling at the aggregate level. It is true that the Kuznets elasticities for production-based emissions is somewhat lower than that for consumption-based emissions. This suggests that Brazil's role in the world trading system need not be a big barrier to its ability to reduce emissions growth. We also show that using state level data is a good source of further evidence on the prospects for decoupling. Although most of the states have positive Kuznets elasticities, we show there exist some with negative and statistically significant elasticities, pointing to decoupling. That being said, in Brazilian states we cannot unequivocally say richer states (measured in real income per capita terms) show higher signs of decoupling vis-à-vis poorer ones. The cyclical elasticities differ across states (but they are overwhelmingly insignificant, suggesting short run acyclicality) but understanding the drivers of these differences requires further research.

To summarize, giving the size of Brazil's economy, aiming to put the country on a sustainable carbon trajectory requires a much more disaggregated look than has been the case in previous research. Indeed, signs of the decoupling between emissions and GDP are starting to emerge at the state level. At a time when subnational entities are taking the lead in tackling climate change (such as recently with U.S. states and cities, following the federal decision to pull out of the Paris Agreement), these results point to states where low-carbon policies could be more effective. Policies taming emissions during business cycle upswings could further contribute to achieving Brazil's intended emissions target.

In future work, it would be interesting to link changes in the Kuznets elasticity to the rebalancing of the Brazilian economy. More specifically, one could explore to what extent the transition from manufacturing to services had contributed to decoupling growth and GHG emissions. The state-level analysis used in this paper could be well suited for such a question.

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