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The Spatiotemporal Dynamics of Soybean and Cattle Production in Brazil

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Abstract: The expansion of agricultural frontiers in Brazil has caused substantial changes in land use and land cover. This research aims to analyze the space-time dynamics of soybeans and cattle production in the Brazilian territory during the period 1991–2015. The spatial analysis adopted the following procedures: (a) The change vector from the annual calculation of the midpoint of production; (b) mapping of the growth and acceleration rates of the two productions, and (c) mapping of the correlation between the time series of soybean and cattle. The results showed high rates of growth and acceleration for soy production in the South, Central-West and Matopiba regions. The growth acceleration rate identified the long-term deviations that characterized the effective soybean and cattle expansion areas. The results demonstrated the effects of Brazil's soy moratorium contained soybean expansion into the Amazon region. However, as a side effect, the soybean production replaced cattle production in the savanna region, which in turn, migrated to the Amazon rainforest. Therefore, the present study highlights the importance of public policies that comprehensively understand the spatial-temporal dynamics of Brazilian agriculture to promote sustainable land-use practices.

Keywords: soybeans; cattle; growth rate; growth acceleration; correlation; agricultural production; land use change; agribusiness

1. Introduction

The growing demand for agricultural products has caused commercial expansion in emerging countries. For instance, since 2002, China has increased imports of raw materials and food from Latin America. Thus, this region has become the most significant food exporter, with considerable growth in production, overcoming sustained consumption growth [1]. In this context, Brazil stands out because it has vast reserves of natural resources and a vocation in the production of primary commodities [2]. The excellent performance of Brazilian agricultural in the global market is due to the combination of technologies focused on development and productivity [3].

Among the main Brazilian export products are soybeans and beef cattle. The soybean production has an international market composed of four main players, three producers (the United States, Brazil, and Argentina), and a large importer (China). Brazil has a total area of 851 million hectares, of which 282 million are destined for agriculture. Soybean crops occupy most of the cultivated areas, about 32 million hectares [4]. In 2014, Brazil exported the greatest amount of soybean and was the second largest producer in the world [5]. Brazilian soybean crop production increased by 74.8% in the last ten years, with an area increase of 40.4% and productivity of 24.5% [6]. The country also invests in the diversification of its energy matrix using soy derivative products. More than 42% of energy is renewable and the main of its liquid biofuels used are ethanol and biodiesel, in which almost 81.3% of biodiesel production comes from soybean oil [7].

However, countries such as Brazil, with strong representation in the agricultural export market and land availability, have a dilemma between the sustainability of ecosystems and the increase of food productivity. The high-yield and profitability of farming systems act as an incentive for the expansion of agricultural frontiers [8]. Thus, the extensive cultivation area used for export crops has caused substantial transformations in Brazil land use and land cover. The growth of large-scale agriculture has been associated with widespread degradation of Brazilian ecosystems, mainly in the Cerrado and Amazon Rainforest, causing inequality in the land distribution in Brazil [9].

The debate about the role of soybean cultivation in the deforestation of the Amazon resulted in the declaration of the soy moratorium on 24 July 2006, with the objective of inhibiting the advance of the soybean crop over the Amazon forest. The regulatory mechanism is based on an agreement between federal banks and companies to not buy soy and not provide credit to producers that deforested their farms after July 2006. In this agreement, the increase of soybean plantation should occur only in areas already deforested and not on natural Amazonian habitats. The new Forest Code (25 May 2012)—established 22 July 2008 as the reference date of the moratorium—required adherence from the 2012/13 harvest. This policy, throughout the decade from 2010, was effective, excluding the expansion of soybean plantations that occurred in deforested areas after July 2008. However, the expansion of soybean production for biofuel production and animal feed has directed cattle farming to new areas, such as the southern border of the Amazon Forest [10–13]. Therefore, agricultural expansion can indirectly move other activities to the forest frontier. Moreover, the surveys for the period showed that most of the Amazon deforestation was due to pasture farming, although forest-to-soybean conversion also occurred [10,14,15].

Recently, McManus et al. [16] perform a spatiotemporal analysis of Brazil's cattle production in the 1977–2011 period, showing its movement to the northern region of the country from the mapping of the growth rate and acceleration of production using geographic information systems (GIS). The GIS aids understanding of production systems, enabling identification of appropriate areas for agricultural expansion, detection of land-use change, and evaluation of environmental and socioeconomic variables with production [17,18].

The present research seeks to complement the studies developed by McManus et al. [16], evaluating the spatiotemporal relationship between soybean and cattle production. The objectives of this research are to (1) analyze the space-time dynamics of soybean production in the Brazilian territory in the period 1991–2015, determining the rate of growth and its acceleration, and (2) evaluate the process of replacing cattle with soybeans, considering correlation maps between both production time series. This new approach of spatializing the correlation indices between the time series of the two productions can detail where this replacement phenomenon occurred more intensely.

2. Materials and Methods

We used the time series of municipal data from the Brazilian Institute of Geography and Statistics [4] for the amount produced in tons of soybeans and cattle herds between 1991 and 2015. The spatial analysis of the data used the ArcGIS 10 software. The methodological steps were as follows: (a) Spatial analysis of the midpoint of soybean and cattle production (latitude and longitude) over time; (b) mapping the growth and acceleration of municipal production of soybean and cattle; and (c) spatial analysis of cattle replacement by soybean from the correlation map between the time series of the acceleration values from the two productions. A flowchart shows the methods steps (Figure 1).

The annual midpoints of soybean and cattle productions over the study period describes the migration trend of these products in the Brazilian territory. The calculation of the coordinates used the following Equations (1) and (2) [19]:

$$Average\ Latitude = \frac{\sum(latitude\ \times production)}{\sum production} \quad (1)$$

$$Average\ Longitude = \frac{\sum(longitude\ \times production)}{\sum production} \quad (2)$$

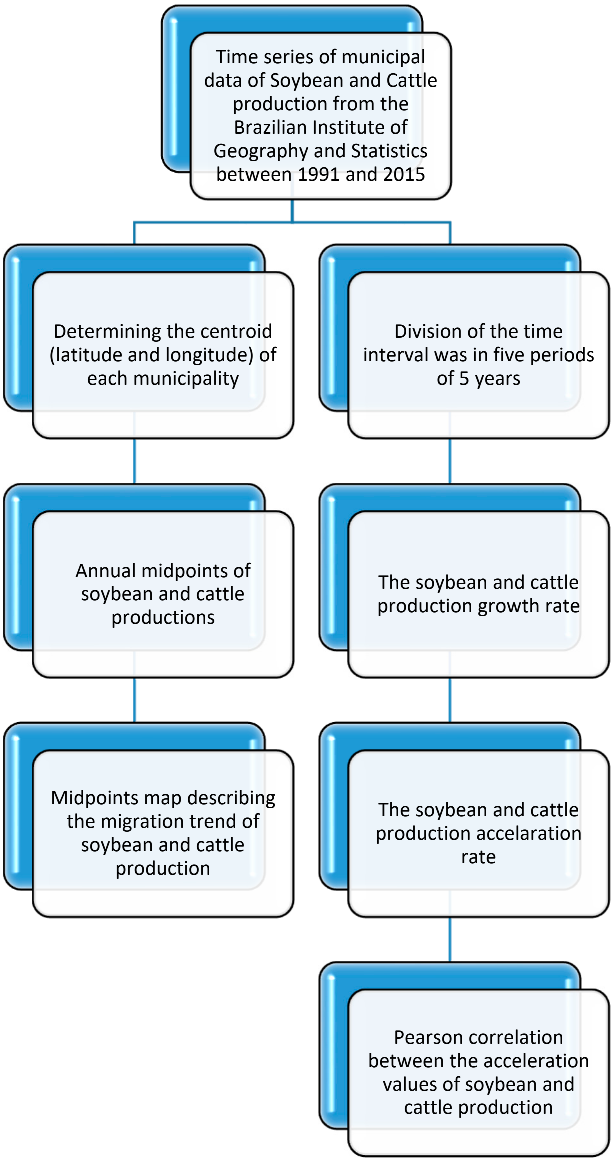

Figure 1. Flowchart shows the steps and methods followed in the study.

The soybean and cattle production growth rate between 1991 and 2015 describes percentage variation of production per municipality. The division of the time interval was in five periods of 5 years (sum of 5 years of production in each period: 1991 to 1995, 1996 to 2000, 2001 to 2005, 2006 to 2010 and 2011 to 2015). The sum production of these intervals better showed the evolutionary dynamics of production. The calculation of the growth rate used the Equation (3) [19,20], resulted in four periods (1991 to 2000, 1996 to 2005, 2001 to 2010, and 2006 to 2015).

$$\frac{(Production\ in\ Present\ Period - Production\ in\ Previous\ Period)}{Production\ in\ Previous\ Period} \times 100 \quad (3)$$

The acceleration estimate of soybean and cattle production was the difference between the absolute values of the growth of the current period with the previous period [19,20]. The acceleration of production resulted in three periods: 1991 to 2005, 1996 to 2010 and 2001 to 2015 (Figure 2).

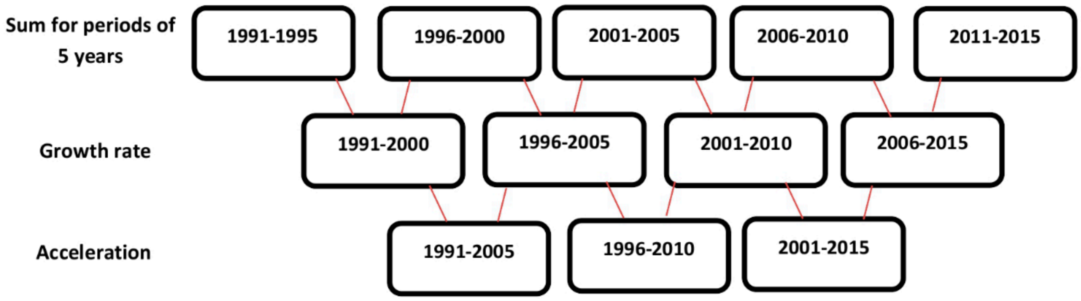

Figure 2. Procedure for the elaboration of the growth rate maps (percentage variation) and acceleration of soy production.

Finally, the analysis of the association (positive correlation) or substitution (negative correlation) of cattle by soybean adopted the Pearson correlation between the acceleration values of these two variables in the period 1991–2015. Equation (4) represents the Pearson correlation coefficient:

$$r = \frac{\sum_{i-1}^{n}(x_1 - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \cdot \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (4)$$

where $x_1, x_2, \ldots, x_n$ e $y_1, y_2, \ldots, y_n$ are the measured values from both variables.

The determination of the municipalities with the conversion from cattle to soybean considered two aspects: (a) The cattle heads production per municipality above 100,000 in 5 years, and (b) $r \leq -0.3$. This procedure avoided selecting municipalities that have cattle-soybean conversion but are very small.

3. Results

The annual midpoints of soybean production in the period 1990–2015 showed a trend of displacement from the South to the Central region of the country (Figure 3). The midpoint of 2005 reached the northernmost position of the country, the year before the soybean moratorium, which evidenced the immediate result of the adopted policy. The state of Mato Grosso was mainly responsible for the regional displacement, becoming the leader of soy production and productivity in Brazil. This change did not exclude the high relevance of soybean cultivation in the South region, which was the largest producer in 1990 with 11 million tons [4] and the second in 2015 with 35 million tons, behind the Central-West region (43 million tons).

Cattle production midpoint in the period 1990–2015 showed a continuous trend of displacement from Southwest to Northwest (Figure 3). In 1990, the largest cattle producers were Minas Gerais, Mato Grosso do Sul, Goiás, and Rio Grande do Sul, concentrating the production in the Center-South of the country. In 2015, this scenario changed and states such as Pará and Rondônia began to stand out among the largest states of cattle production [4].

Figure 4 shows the growth rate maps of soybean production. Throughout the period, the soybean plantation had a constant expansion mainly in the Central-West, Southeast and South regions. The growth rate maps show a momentary and punctual variation, occurring over time reducing production in part of the Southeast and Central-West region mainly in the periods 1991–2000 and 2001–2010. The map of the average growth rate of soybean production pointed to many high-growth municipalities, mainly in the South, Central-West and Matopiba regions.

The comparison of the acceleration maps of soybean and bovine production demonstrates the replacement of cattle by soybeans in Central Brazil during the analyzed period (Figure 5). The municipalities with the greatest prominence of this change occurred in the states of Mato Grosso, Mato Grosso do Sul and Matopiba. Concomitant to the exit of cattle in the Central-West region, production appeared in the North region (Rondônia, Amazonas and Pará), evidencing its displacement to the Amazon forest.

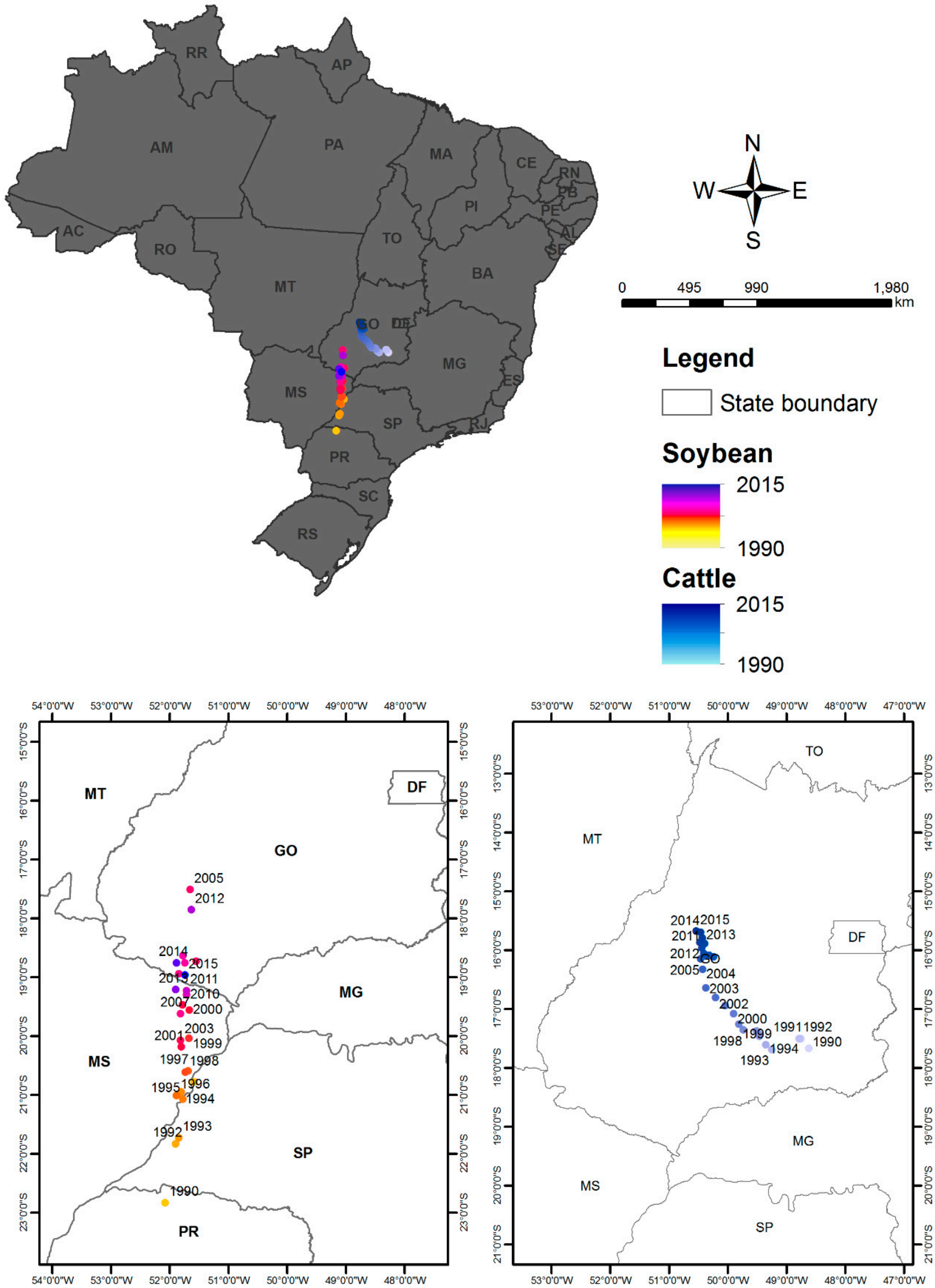

Figure 3. Midpoint of soybean and cattle production in Brazil from 1990 to 2015.

Growth acceleration maps provided a clearer distinction of areas of agricultural expansion and were more profitable in detecting abrupt changes than the growth rate map. Acceleration allowed the elimination of the uniform growth trend from productivity gains and highlighted hotspots from the expansion of areas. The high volatility of the growth rate may result in poor performance by not capturing the long-term patterns, while acceleration can yield more relevant results by examining the causes of deviations from the long-term trend.

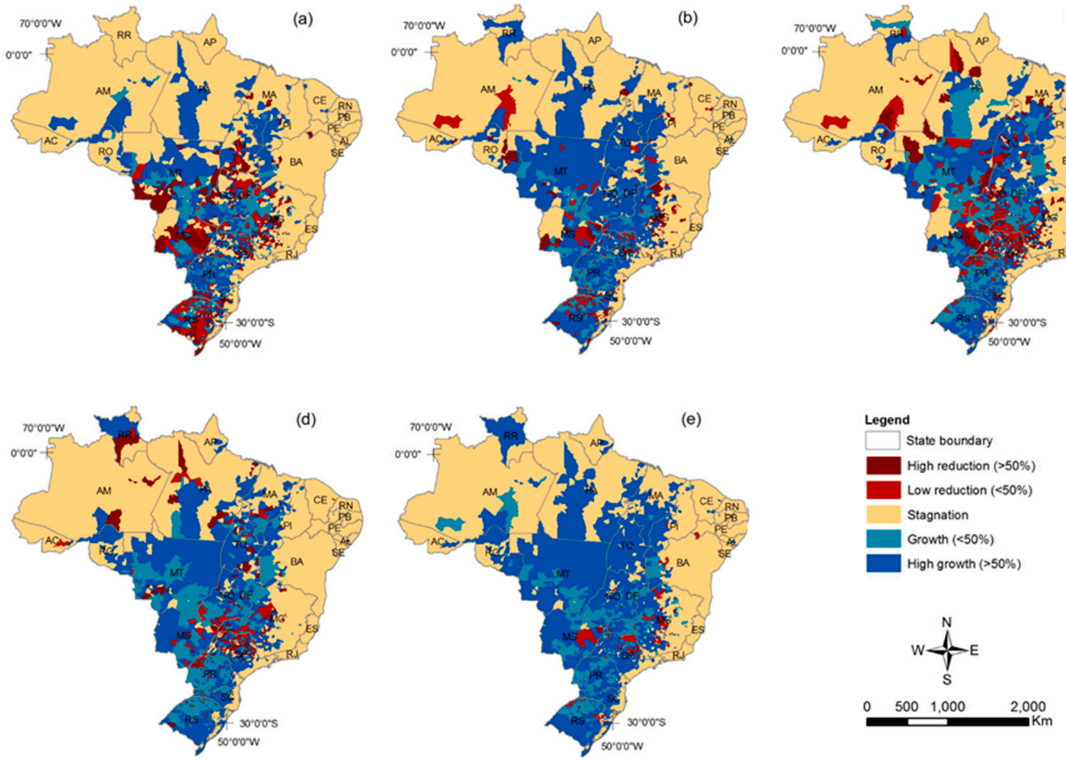

Figure 4. Growth rate of soybean production in Brazil. (**a**) 1991 to 2000; (**b**) 1996 to 2005; (**c**) 2001 to 2010; (**d**) 2006 to 2015; (**e**) average growth rate.

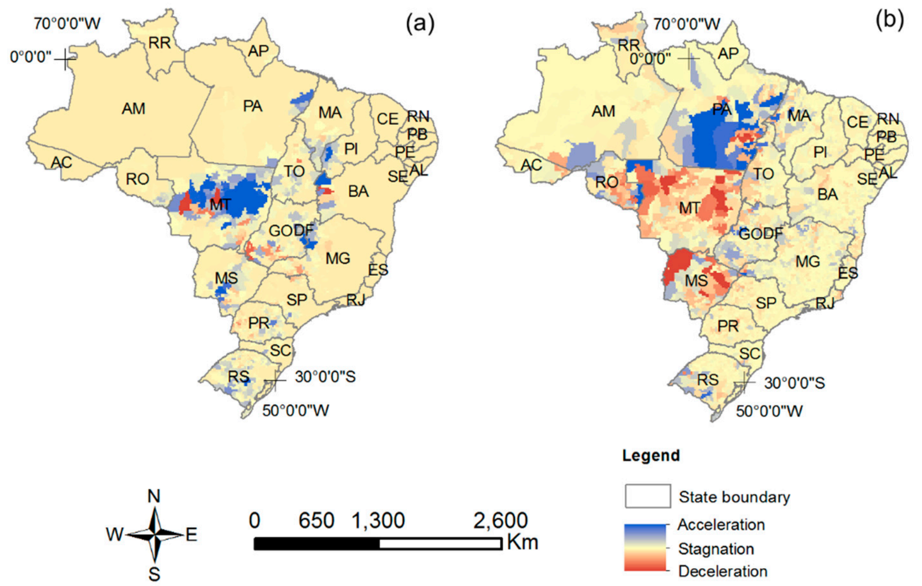

Figure 5. Average growth acceleration map of soybean (**a**) and cattle (**b**) in Brazil for the period 1991–2015, considering the values from the periods 1991–2005, 1996–2010, and 2001–2015.

Figure 6 shows the correlation map between the growth acceleration rates of soybean and cattle production. Many municipalities presented a direct correlation, mainly in the north of Rio Grande do Sul, where the two types of productions rise or fall together. Municipalities with an inverse correlation may be due to the replacement of soy by cattle or vice versa. The municipalities with pasture-to-soybean conversion predominated in the states of Mato Grosso do Sul, Mato Grosso, Goiás, and eastern Minas Gerais. Unlike, the inverse correlation of the states of Pará and Rondônia was due to the growth of pasture production.

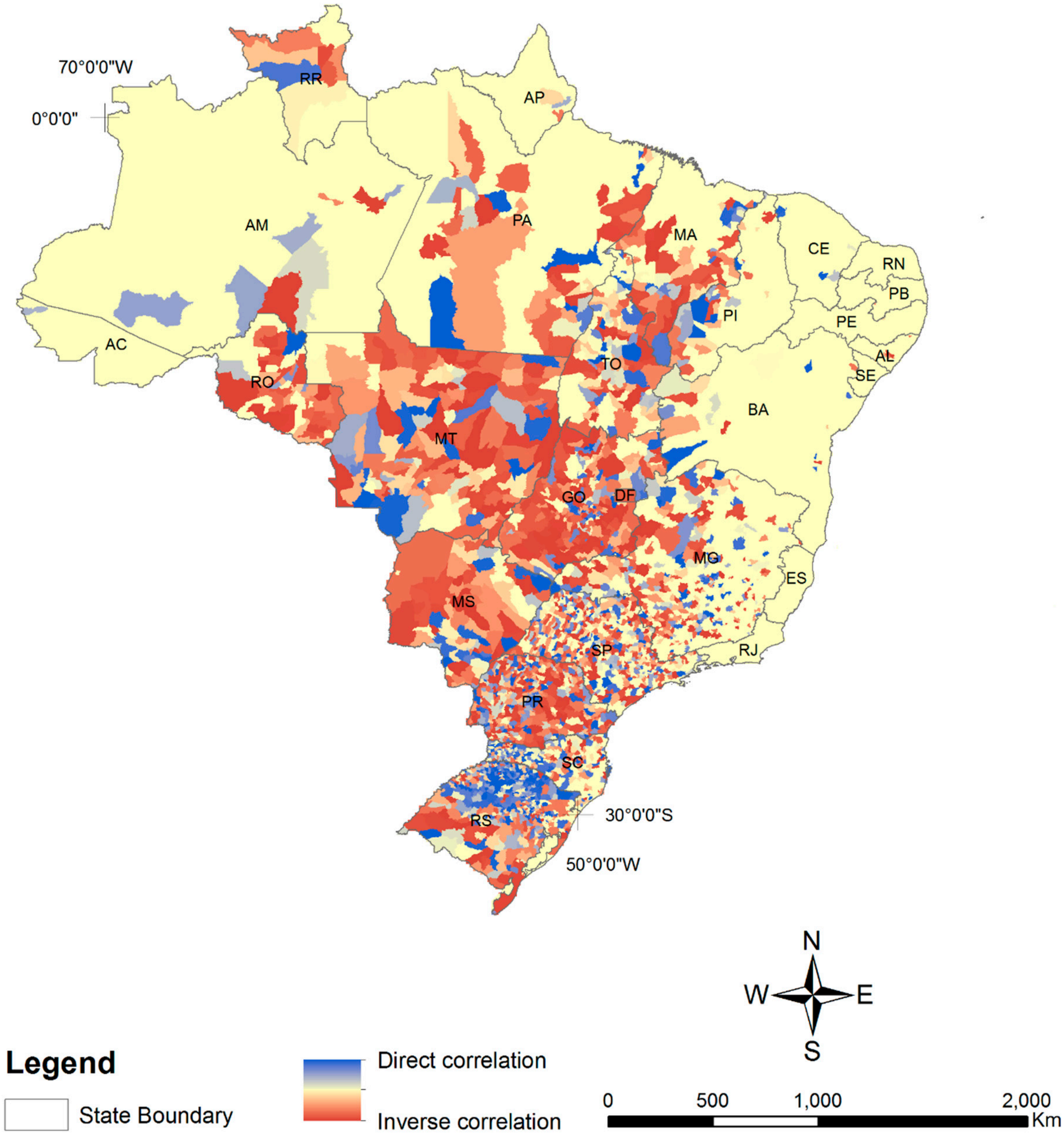

Figure 6. Correlation between acceleration of soybean and cattle production by municipality from 1991 to 2015.

4. Discussion

The growth and acceleration maps of soybean production emphasized the traditional regions in the South, Central-West and later in the Matopiba region. The municipalities of the State of Mato Grosso were prominent producers, due to the high extension of cultivated area and the use of advance technology in the production, which registered high productivities. The soybean expansion to the Central-West in the last decades has been linked to modernization policies: Credit availability; rural extension; biological nitrogen fixation; conservation practices (e.g., direct planting); expansion of irrigation systems; and agricultural research support mainly by the Brazilian Agricultural Research Corporation (EMBRAPA) to develop plant varieties adapted to the climatic and pedological conditions [21–24].

During the 1990s, the creation of the Kandir Law to stimulate exports and reduce the final price of the product brought tax exemption on exports of primary commodities [25]. Furthermore, the financing and investment programs in the second half of the 1990s (for example, the Modernization Program of the Farm Tractor Fleet and Associated Implements and Harvesters and the National Program for Strengthening Family Farming) encouraged the acquisition of new machinery and equipment for agricultural production [26]. The high acceleration and growth rate of soybean production during the period 1996–2005 came from volatility in food prices, known as the commodity boom. Several factors contributed to this scenario, such as world demand growth (which has surpassed production); the reduction of grain stocks; climate change impact on agricultural incomes in Russia, Kazakhstan, Canada, Australia and Argentina; the high price of crude oil that stimulated the use of food commodities to generate biofuels; and greater participation of grains from the Black Sea and Latin America [27].

The financial crisis of 2008 had a differential impact on developed and emerging countries. The international trade flows among developing countries began to be intensified, constituting a new dynamic for Brazilian agriculture, with exports and imports to China, Russia, and India. In the recent decade, China's demand for raw materials has grown faster than domestic production [28]. Soy is the main ingredient in Chinese food products, but its direct consumption is small when compared to the widespread use of soybeans for animal feed, intensifying the demand of the product in international trade [29].

Therefore, the increase in the price of grains on the global market and the massive public investment in infrastructure, with the improvement of railroads, waterways, and highways (for example, Madeira River waterway, part of the North-South railroad, BR-333 and BR-163 highways) provided a rapid expansion of the soybean crop [30]. Recent export routes from northern fluvial ports (Barcarena and Santarém) have changed grain transport dynamics by gaining competitiveness in the link from north Mato Grosso (MT) to China, Europe, the Middle East, and Mexico [31]. This northern gateway increased the competition and created new opportunities for farmers in the Central-West and Matopiba regions and reached 25% of soybean exports in 2018 [31]. This combination of factors led to the Brazilian soybean production to match North America in the harvest of 2012/2013. In the period 2014–2015, Brazil was China's largest supplier of soybeans with total exports reaching 36.4 million tons and occupying 47% of the market [32].

The soybean moratorium showed efficacy in the stagnation of the forest-to-soybean conversion in the Amazonian environment. In the 2016/2017 harvest, the soybean plantation in the Amazon region occupied an area of 4.48 million hectares, where only 47.365 hectares did not comply with the soybean moratorium rule [33]. In the Amazon region, the monitoring of soybean plantation uses remote sensing satellite images (the MOD13Q1 product and TM/Landsat-5 images), aerial surveys and field inspection [34].

However, savanna areas outside the protection zone of the soy moratorium became a target for the soybean advance, with even greater expansion attractiveness, for example, the best infrastructure for the flow of the agricultural crop [35]. The soybean moratorium and the rising commodity prices on the international market encouraged cattle ranchers in savanna environments to sell their land and migrate to other less structured places [36]. In this context, the Matopiba region consolidated as a hotspot of the new agricultural frontier in Brazil due to savanna environmental conditions. The Brazilian institution calculates the cost of land, based on an agricultural census of the Brazilian Institute of Geography and Statistics and also in questionnaires applied to farmers and realtors [37]. The states of Matopiba had a lower price than the Central-West region. In 2014, the cost of high-productivity land in the Central-West region was 163.5% higher than in the Northeast region and 454.8% higher for low-productivity land [37]. However, part of the agricultural expansion in Matopiba occurred by the direct conversion of native vegetation to soybean, which made the remaining natural vegetation highly susceptible to soybean conversion due to the lack of safeguards [38].

In the regional balancing of commodity productions, the cattle activities moved from the Central-West region towards the Amazon as a result of agricultural expansion, resulting in the increase of the size of the cattle herd in the legal Amazon [39]. This administrative region, delimited by the Brazilian government for sustainable development planning, comprises nine Brazilian states with similar social and economic problems. Cattle farming in the Amazon provides an increase in the value of land to be cleared and facilitates the acquisition of land ownership [11]. In addition, there is an expectation of increasing land prices due to improvements in infrastructure and demand for food commodities. Thus, the Central-West region is demarcated by the inverse correlation of their growth acceleration rates due to the increase of soybeans and the reduction of cattle. In contrast, the municipalities of Rondônia, southern Amazonas, Pará, Maranhão, and northern Mato Grosso presented higher growth acceleration rates of cattle production. This spatial subdivision of the country, with the intensification of pasture in the North region and the soybean plantation in the Central-West region, can be interpreted as being complementary parts of the same dual expansion front system [40]. The growth acceleration rates and correlation maps of the two production systems demonstrated the strategies of joint expansion with the soybean-pasture coupling.

Although the expansion of the 2000s is difficult to replicate, price volatility and demand for commodities may lead to price increases similar to the period of the commodity boom triggering a new wave of deforestation in the forest and savannah [41], considering soybean-pasture coupling. Thus, financial support, other policy/regulatory instruments, and incentives that aim to stimulate production on a more sustainable basis and the conservation of native vegetation can play an essential role in the convergence of environmental preservation and economic growth. Dias et al. [42] concluded that the extension of Brazil's agriculture and cattle production declined. These authors affirmed that in recent years, there has been a considerable intensification in agricultural production. In the Amazon region, soy production almost doubled per hectare between 1990 and 2012. In the same period, cattle production, also in the Amazon, increased by about 2.5 times the number of heads per hectare. This behavior of land use and land cover change contributes to the increase of production without any increase in the agricultural frontier.

The already degraded areas in the national territory of Brazil, estimated at 50 million hectares, could be dedicated to increasing the agribusiness sector from the appropriate management and soil recovery [43]. Furthermore, the adoption of integrated systems, such as crop-cattle or crop-cattle-forest integration, which are more sustainable than specialized (monoculture) systems, can help meet the growing demand for food, fiber and bioenergy, the expansion of pasture areas and reducing the negative impact on ecosystems and agrosystems [44,45]. Moreover, new proposals are being evaluated to contain deforestation, such as the soybean moratorium in the savannah region or even the livestock moratorium in the Amazon region. Government policies should consider a single system with different production relations to establish sustainability land-use rules and laws [46].

5. Conclusions

The present research innovates in the soybean-cattle substitution analysis from the spatial distribution of the temporal correlation between the production time series. The temporal correlation map synthesizes the spatiotemporal dynamics of soybean and cattle production in Brazil, which expands in a coupled way to the regions of savannah and Amazonian forest. Thus, this research advances the studies of McManus et al. [16], who evaluated cattle production, including the spatiotemporal dynamics of soybean and its correlation with cattle production. Soybean expansion shifted cattle production from the savannah regions to the Amazon forest, showing an inverse correlation between the two-temporal series. This couple expansion has driven accelerated changes in land use, intensification of social conflicts and deforestation pressure on the border with the Amazon. The soybean moratorium induced this regional compartmentalization of production, since it controls the advance of this planting in the Amazon region and concentrates the production in the municipalities of the South, Central-West, and Matopiba, which demonstrated a high rate of growth and acceleration of production during the analyzed period. Thus, Brazilian soybean production stands out in the international market due to productivity gains and the incorporation of new agricultural frontiers. This prominence in world agricultural scenario reinforces the importance of the impacts of technologies in production systems and the participation of finance and investment programs. In addition, the development of an infrastructure for the export route and lower land prices in the Matopiba region are factors that have encouraged soybean growth in Central Brazil. Public policies in the face of this complex phenomenon will have the challenge of increasing productivity to meet national development and conserve natural environments. Our method enables identification of the location, magnitude, dynamics, and interrelations of soybean and cattle production, being useful in the decision making of governmental actions.

Author Contributions: R.L.A.M. participated in the conception of ideas for the elaboration of the article, conducted the research and prepared the initial essay. O.A.d.C.J. developed methods of acceleration and growth of cattle and soybean production, managed research in writing, reviewing, and editing. P.M.H. participated in the application of statistical methods and the formulation of objectives, carried out important experiments to validate the methodology and assisted in the final revision of the text. R.A.T.G. validated the research for reproduction of the results and participated in the preliminary writing. C.M.M.P. participated in the formulation of the research objectives, assisted in the preliminary and final writing, as well as the revision and editing. R.F.G., the corresponding author, worked on the application of statistical methods to analyze cattle and soy production and conducted the research process performing data collection.

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