Alternative Scenario Simulation for Urban Sprawl Based on Population Dynamics: A Methodological Proposal

Adriano Bressane [1]
Maurício Tavares da Mota [2]
Felipe Hashimoto Fengler [3]
José Arnaldo Frutuoso Roveda [4]
Sandra Regina Monteiro Masalskiene Roveda [5]
Gerson Araujo de Medeiros [6]
Admilson Írio Ribeiro [7]

ABSTRACT

The urban sprawl implies in the reduction of rural production areas and increases the pressure on the natural spaces. Hence, if the urbanization does not occur properly, it can compromise sanitary conditions, biodiversity, resources and environmental services. This paper aims at presenting a mathematical model to support urban sprawl based on population dynamics, applied as a case study in the Economic Hub of the Metropolitan Region of Sorocaba - MRS. The materials corresponded to census data and urban planning parameters of the applicable law. As a result, it was found that the urban extension of Sorocaba is oversized, and that the maintenance of the current conditions and guidelines will have critical consequences, requiring a change in local politics. We conclude that the proposed model can support strategic decisions, preventing problems related to disordered growth.

Keywords: Modelling; Zoning; Management.

[1] Doutorado em Ciências Ambientais pela Universidade Estadual Paulista Júlio de Mesquita Filho, UNESP, Brasil. Professor na Universidade Estadual Paulista Júlio de Mesquita Filho, UNESP, Brasil. adriano.bressane@unesp.br
[2] Doutorado em Ciências Ambientais pela Universidade Estadual Paulista Júlio de Mesquita Filho, UNESP, Brasil. Professor na Secretaria de Estado da Educação, SEE, Brasil. mauriciotavaresmota@gmail.com
[3] Doutorado em Ciências Ambientais pela Universidade Estadual Paulista Júlio de Mesquita Filho, UNESP, Brasil. Professor na Faculdade de Engenharia de Sorocaba, FACENS, Brasil. felipe.fengler@posgrad.sorocaba.unesp.br
[4] Doutorado em Matemática pela Universidade de Brasília, UnB, Brasil. Professor na Universidade Estadual Paulista Júlio de Mesquita Filho, UNESP, Brasil. roveda@sorocaba.unesp.br
[5] Doutorado em Matemática pela Universidade de Brasília, UnB, Brasil. Professor na Universidade Estadual Paulista Júlio de Mesquita Filho, UNESP, Brasil. sandra@sorocaba.unesp.br
[6] Doutorado em Engenharia Agrícola pela Universidade Estadual de Campinas, UNICAMP, Brasil. Professor na Universidade Estadual Paulista Júlio de Mesquita Filho, UNESP, Brasil. gerson@sorocaba.unesp.br
[7] Doutorado em Engenharia Agrícola pela Universidade Estadual de Campinas, UNICAMP, Brasil. Professor na Universidade Estadual Paulista Júlio de Mesquita Filho, UNESP, Brasil. admilson@sorocaba.unesp.br

In the last decade, the world's urban population exceeded the rural one for the first time in history. With the urban sprawl and the concentration of population in the cities, food needs are growing, whilst the food sovereignty and safety tends to weaken (FAO 2011; FAO 2013; He et al. 2017). In Brazil, the urbanization is a relatively recent phenomenon, especially after the second half of the twentieth century, articulating a set of changes in the economy, society and national politics (Brito 2006). While in 1960 the rural population was still dominant, according to the last census more than 84% of the Brazilian population lived in urban areas (IBGE 2010), pointing out that urbanization has intensified over the last few years.

Although spatial planning is a basic premise for social organization, oftentimes the growth of cities occurs without planning and public policies capable of disciplining land use and occupation, disregarding the demands of population growth. Thus, urban sprawl can become unsustainable, i.e. unable to meet social needs, resulting in the poor quality of life of a significant share of the population (Grostein 2001).

Searching for a more sustainable urbanization, studies have been reinforcing the importance of spatial planning as one of the strategic dimensions for urban and regional development (Monteiro et al. 2014; Peres & Silva 2013; Santos & Raniere 2013). To achieve this goal, among the tools of the Master Plan, urban zoning contributes to discipline human settlements and economic activities and, above all, for supplying the population through sustainable practices in exploiting available resources (Söderman et al. 2012; Santos & Raniere 2013; Rinne & Primmer 2016).

The lack of territorial planning may imply the occurrence of incompatible use and occupation on areas of environmental, archaeological or cultural interest, by favouring a real estate speculation and causing unbridled reduction of productive areas (Maricato 2013; Partidário 1999). Hence, disordered urban sprawl can aggravate the suppression of natural areas with consequences on the climate (Morelli et al. 2012), such as the occurrence of extreme events, including droughts and prolonged droughts, as observed by Nobre (2016). This expansion over the peri-urban areas may lead to a less permanent rural lifestyle, especially as regards social organization and reduction of productive potential in municipalities, intensifying the risk of social exclusion, impoverishment and rural exodus (Brandemburg 2010). Besides, food security of the municipalities would be compromised as well as the preservation of natural conditions favorable to biodiversity and the water resources for human consumption (Fengler et al. 2015; Souza & Brandenburg 2010; Santoro & Pinheiro 2004).

Urbanization also raises occupancy rates, increasing the proportion of built-up areas and, consequently, implies a greater superficial waterproofing and respective reduction of water infiltration into the soil. As a consequence, there is a greater run off and evaporation, decreasing ground water recharge and intensifying flooding, water scarcity, damage to property and public health (Soares et al. 2014; Menezes Filho & Tucci 2012; Bierwagen et al. 2010; Tucci 2008). Another aspect related to urbanization is the degradation of water resources by dumping of wastes, domestic and industrial sewage (Medeiros et al. 2017; O'Neill et al. 2013; Salles et al. 2012; Zeilhofer et al. 2010; Jamwal et al. 2008)

The absence of land-use control mechanisms still favor real estate speculation, seeking land valorization by converting it into urban areas, based on public investment in infrastructure (Maricato 2013). This way, despite the need for urban expansion to support the economic and social context it should be conducted carefully. Therefore, the study of population dynamics can be of great importance, since the demographic growth and its distribution bring significant implications to the territory, such as vegetation removal, soil sealing, overloading the infrastructure and services, among others (Hogan 2010).

An important indicator for the study of this dynamic is the population density, which relates the population size to the occupied area (Acioly & Davidson 1998). Among the main references for this indicator there are the United Nations (UN) and the American Public Health Association (AASP), which recommend 450 inhab. ha^{-1} and 680 inhab. ha^{-1}, respectively (Rodrigues 1986). In Brazil, the average population density increased from 0.11 inhab. ha^{-1} in 1970 to 0.22 inhab.ha^{-1} in 2010, doubling in the last four decades. Considering some Brazilian cities, the average population density reached 0.13 inhab. ha^{-1} in Porto Velho, in Amazonian region, 71.67 inhab. ha^{-1} in Belo Horizonte and 73.88 inhab. ha^{-1} in Sao Paulo, both located in southeast region, and 77.88 inhab. ha^{-1} in Fortaleza, in northeast one (IBGE 2010).

In relation to territorial planning, the gross density can be even more efficient, considering only the area calculated from the administrative limit of which are discounted the areas of sporadic use. In general, this relationship between the size of the population and the occupied area becomes relevant because it impacts on the cost of urban infrastructure and its dimensioning. In addition to the recommendations on population density, it is possible to consider that there are other urban indexes with important purposes, such as the maintenance of permeable areas and the pattern of land use. These indices imply maximum occupancy rates and minimum lot size, for instance.

In this context, this paper presents a model for scenarios planning to support urban territorial expansion in a progressive way. Based on the population dynamics, the proposed model was applied as a case study in the city of Sorocaba, state of São Paulo, economic hub of the newly created Metropolitan Region.

MATERIALS AND METHODS

STUDY AREA

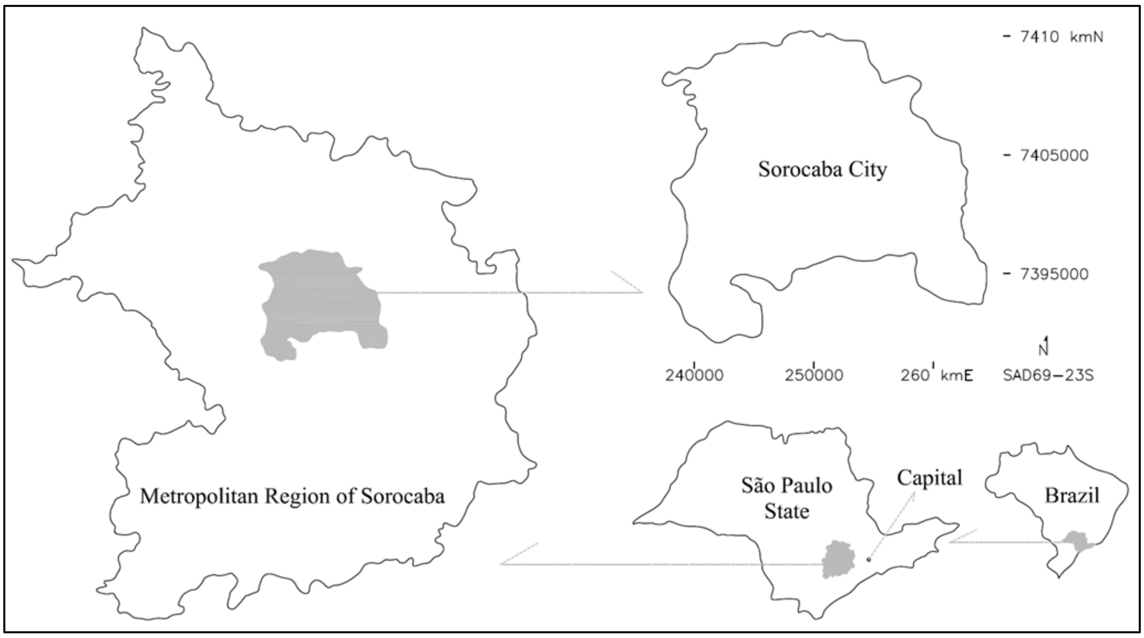
The Metropolitan Region of Sorocaba (MRS) comprises 26 municipalities whit around 1,730,000 people, living in 9,821 km^2, corresponding to a population density of 1.76 inhab. ha^{-1}. The Gross Domestic Product (GDP) from MRS totalizes US$ 14.5 billion or 1.13% of GDP from São Paulo state (EMPLASA 2015).

However, despite the importance for urban and regional development, this MRS formation process tends to increase the economic pressure over natural areas that, currently, have only 12.6% of the original vegetation minimally altered, which is concentrated in the rural zone of Sorocaba (SEMA 2010).

The population from Sorocaba city is of 615,955 inhabitants living in 449.12 km² (Figure 01) (IBGE 2015). Currently, the city is one of the ten largest economies of São Paulo state, presenting a Municipal Human Development Index of 0.798 and holds the thirty-second largest GDP from the Brazilian cities, reaching around US$ 5.9 billion (SEADE 2015). Thus, its economic performance, among other conditions, led the Sorocaba city to become the economic hub of MRS.

Sorocaba city presents favorable environmental indicators when compared to the Brazilian scenario, such as green area, basic sanitation, water treatment, etc. In 2012 Sorocaba Environmental Office (SEMA) reported a green area index of 104.6 m² $inhab.^{-1}$ (SEMA 2012), representing 700% above the minimum (15 m² $inhab.^{-1}$) recommended by the Brazilian Society for Urban Forestation (SBAU 1996). Sorocaba city still stands out among the top five cities regarding basic sanitation in Brazil, with sewage treatment and drinking water distribution reaching more than 90%. However, different indicators of environmental degradation in the municipality have been pointed out by some authors, such as the change in land use and the suppression of wildlife habitats (Silva 2010); the emission of atmospheric pollutants affecting rainwater quality (Conceição et al. 2013); the contamination of soil and groundwater by the disposal of industrial waste (Penkaitis & Sígolo 2012); and dumping of domestic and industrial sewage into water bodies (Silva et al. 2013).

Figure 01. Location of the economic hub of Sorocaba Metropolitan Region.



Source: The Author

Another significant consequence was the advancement of the urban area and respective reduction of the rural zone which, prior to 2004, corresponded to 48.9% of the municipality (Sorocaba 2004), in 2007 to 17.9% (Sorocaba 2007), and with the last revision of the Master Plan was reduced to 14.4% (Sorocaba 2014). Although the last reduction is 3.5% in relation to the municipal territory, it is equivalent to a decrease of 18.1% in the previous extension of the rural area. It should be noted the environmental services provided by rural zone, which have a high impact on human well-being, such as those of provisioning (food, wood, fiber, and water production), regulation (climate control, flooding, nutrients and contaminants filtering, carbon storage, waste recycling), support (soil formation and nutrient cycling) and cultural (landscape, unmarketable benefits) (Dominati et al. 2014).

Environmental conservation areas were also reduced from 20.9 to 11.6 km², by the last review of the Master Plan. It corresponds to a reduction of 45% in the total areas previously located along the main water courses of Sorocaba, which increases the risk of occupying floodplains. As an aggravating factor, current law still reduced the minimum percentage of permeable area, which went from 80% to 20% (Sorocaba 2014). This is a critical aspect in the municipality, which had 157 areas considered of risks, of which 98 corresponded to flooding points on public roads and 57 sites with potential for flooding of buildings (Sorocaba 2017).

METHODOLOGICAL PROPOSAL

To study the population dynamics, it was built a model based on the logistic growth function by Verhulst (1947), which consists of an ordinary differential equation, whose analytical solution corresponds to equation (2):

$$\frac{dP}{dt} = \left(r - \frac{r}{k}P(t)\right)P(t) \tag{1}$$

where $\frac{dP}{dt}$ is the variation of the population over time; $P(t)$ is the population size in the year $t[inhab.]$; r is the growth rate; and k is the population limit.

$$P(t) = \frac{k}{(\frac{k}{P_0} - 1)e^{-r(t)} + 1} \tag{2}$$

Verhulst (1947) proposal is an improvement of the exponential growth theory of Malthus (2004), because it contemplates the simulation of inhibiting factors, such as resource scarcity, defined as support capacity. To construct the model, the coefficients (r, k) were obtained by calculating the average growth rates (r_i), estimated between consecutive census (i and $i + 1$) and their respective averages populations P_i as follows (Bassanezi 2002):

$$r_i = (P_i/P_{i-1})^{1/\Delta i} - 1 \tag{3}$$

Table 01. Average growth rate ($\boldsymbol{r_i}$) and population ($\boldsymbol{P_i}$).

Year	Population	Year	r_i (mean)	P_i (mean)
1940	70,299	1945	0.0294	72,366
1950	93,928	1955	0.0379	97,489
1960	13,6271	1965	0.0249	139,669
1970	174,323	1975	0.0441	182,011
1980	268,396	1985	0.0314	276,816
1990	365,529	1995	0.0305	376,665
2000	493,468	2005	0.0174	502,076
2010	586,625			

Source: Developed by Authors.

For the application in the study area, the main materials used for these calculations were the census data from the Brazilian Institute of Geography and Statistics (IBGE 2010) and the State Data

Analysis System Foundation (SEADE 2015), referring to values available since 1940, at regular intervals of 10 years (Table 01).

To obtain the equation that better relates r_i and P_i, it was applied a curve fitting by the method of linear least squares, given by the following equation (4):

$$A^T A P = A^T R \tag{4}$$

Where

$$A^T A = \begin{vmatrix} \sum_{i=1}^{p} 1 & \sum_{i=1}^{p} P_i \\ \sum_{i=1}^{p} P_i & \sum_{i=1}^{p} {P_i}^2 \end{vmatrix}, A^T R = \begin{vmatrix} \sum_{i=1}^{p} r_i \\ \sum_{i=1}^{p} P_i r_i \end{vmatrix}, P = \begin{vmatrix} a \\ b \end{vmatrix} \tag{5}$$

being a and b, linear adjustment coefficients.

Considering the equations and data described for the present case study, the linear adjustment between r_i and P_i can be expressed by the equation (6):

$$r = a + \ bP = 0.0365 - 2.6488\ 10^{-8} P \tag{6}$$

In turn, from this equation the logistic growth model is given by (7):

$$\frac{dP}{dt} = 0.0365P - 2.6488\ 10^{-8}\ P^2 \tag{7}$$

So, for null variation rate ($\frac{dP}{dt} = 0$), i.e. when there are saturation of support capacity, it can be determined the population ($P = k$) in the limit of growth:

$$0.0365\ k - 2.6488\ 10^{-8} k^2 = K(0.0365 - 2.6488\ 10^{-8}\ k) = 0 \tag{8}$$

Therefore, either $k = 0$ or $0.0365 - 2.6488\ 10^{-8} k = 0$, when $k = 1{,}377{,}982$ inhabitants. Considering these values and t_0 equivalent to 2010, the population dynamics of Sorocaba city can be modeled by the equation (9):

$$P(t_0 + \Delta t) = \frac{k}{(\frac{k}{P(2010)} - 1)e^{-r(\Delta t)} + 1} = \frac{1{,}377{,}982}{1.3733 e^{-0.0365(t-2010)} + 1} \tag{9}$$

For the simulation of the urban expansion scenarios, it was proposed the use of the occupation rate and the size of the lot defined by the current law, the number of inhabitants per household, according to the demographic census, and the estimated population, based on the model of equation (9). In this way, scenarios can be simulated as presented in equation (10) and following:

$$T(t) = \frac{P_u(t)\bar{L}}{\bar{H}\bar{O}} \tag{10}$$

where $T(t)$ is the urban territorial extension in the year t [m^2]; $P_u(t)$ is the urban population size in the year t [$inhab.$]; and L is the average area of lot [m^2/lot], as follows in (11):

$$\bar{L} = \sum_{i=1}^{n} \left(\frac{L_{Zi} Z_i}{A_B} \right) \tag{11}$$

where L_{Zi} is the average area of lot in the zone i [m^2/lot]; Z_i is the area of the zone i for $\forall\ i = (1, 2, \dots, n)$ [m^2]; and A_B is the gross urban area [m^2], as in (12):

$$A_B = \sum_{i=1}^{n} Z_i \tag{12}$$

$\bar{H}$ is the average of inhabitants per lot [$inhab./lot$], given by (13):

$$\bar{H} = \sum_{i=1}^{n} \left(\frac{\bar{H}_{Zi} Z_i}{A_B} \right) \tag{13}$$

where $\bar{H}_{Zi}$ is the average of inhabitants per lot in the zone i [$inhab./lot$]; $\bar{O}$ is the average rate of maximum occupancy [*dimensionless*], as follows:

$$\bar{O} = \sum_{i=1}^{n} \left(\frac{O_{Zi} Z_i}{A_B} \right) \tag{14}$$

where O_{Zi} is the rate of maximum occupancy in the zone i [*dimensionless*].

For the study area, the data used in the modeling of urban planning parameters are organized in Table 02.

Table 02. Parameters for urban territorial simulation of Sorocaba city: Z_i - area of the zone i; L_Zi - average area of lot in the zone i; H ̅_Zi - average of inhabitants per lot in the zone i; O_Zi - rate of maximum occupancy in the zone i.

ZONE		Z_i [m^2]	L_{Zi} [m^2/lot]	$\bar{H}_{Zi}$ [$inhab./lot$]	O_{Zi} [*dim.*]
Central		10,727,238	200	1.88	0.80
Predominantly institutional		3,623,830	360	3.15	0.60
Residential	1	6,449,787	360	3.23	0.60
	2	83,090,560	300	3.23	0.60
	3	87,077,794	200	3.56	0.70
	3 (expanded)	25,852,034	200	3.42	0.70
Urban small farms		89,855,415	1,000	3.22	0.35
Environmental conservation		11,743,343	6,000	3.76	0.20
ZONES		A_B [m^2]	$\bar{L}$ [m^2/lot]	H [$inhab./lot$]	$\bar{O}$ [*dim.*]
Gross urban area		318,420,000	670.8	3.31	0.56

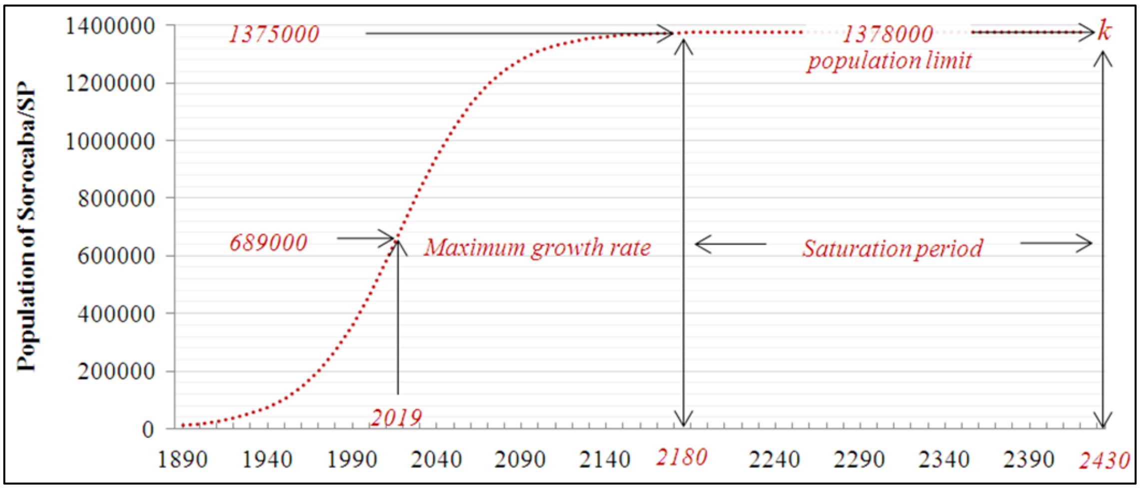
Source: Developed by Authors.

It is noteworthy that for the totalization of gross urban area it was excluded the extension of green areas considered of sporadic use, defined as botanical gardens, zoos, parks, hydric and permanent preservation areas, as well as industrial use ones. According to Mello et al. (2014), the permanent preservation areas amount to 8,499 ha, and the others correspond to 1,594 ha (Mota et al. 2014), totaling 10,093 ha, or 22.3% of the municipal territory. Therefore, the gross urban area of Sorocaba city, considering the current Municipal Master Plan, excluding the aforementioned areas, corresponds to 318.42 km² (31,842 ha).

Results and Discussion

By using the logistic model based on the equation (9), the limit population for the Sorocaba city was calculated at around 1.38 million, to be achieved in 2180 (Figure 02).

Figure 02. Population dynamics projection of Sorocaba/SP.

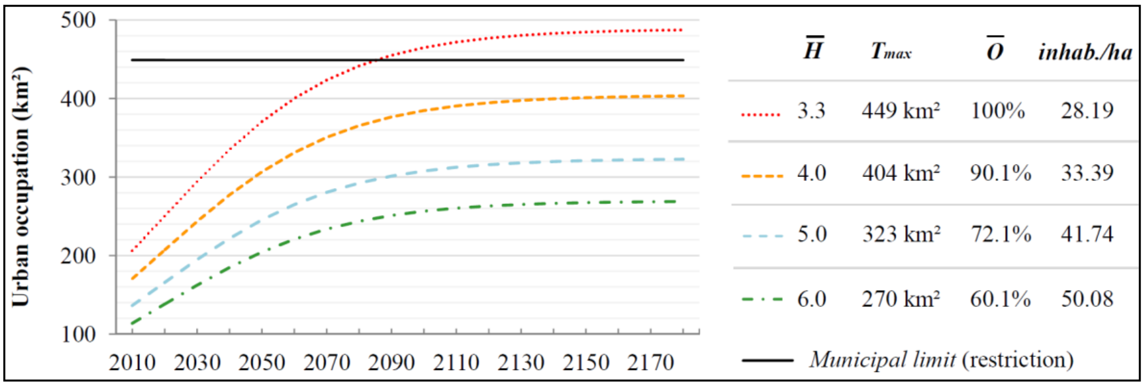


Source: Developed by Authors.

Current population of Sorocaba city has been growing close to its maximum rate estimated for 2019, when it will reach about 689,000 inhabitants. The population begins to stabilize around 2180, when starts the period of saturation achieved in the 2430. Taking into account this projection of population growth and that 98.9% inhabitants living in the urban area (IBGE 2010), the simulation of territorial occupation can be projected based on equation (10). Thereby, it was observed that nowadays the territorial occupation by urban population is approximately of 220 km², equivalent to only 69.2% of the total urban area legally established by the Master Plan, therefore it is oversized for the present conditions. On the other hand, if such conditions are maintained over time, urban parameters of the current law will imply the full occupation of the municipal territory by the urban population around 2085, when it would be achieved about 1.26 million people, corresponding to a population density of just 28.2 inhab. ha^{-1}. This result is relatively low considering Sorocaba city importance in the regional economic scenario, outstanding the need of changes in the land use management.

In this setting, an alternative would be the implementation of public policies that increase the coefficient of soil occupation and, consequently, the density of inhabitants per lot, like vertical building, among other measures, as in the simulations shown in Figure 03.

Figure 03. Simulation of urban territorial occupation in Sorocaba/SP: $\overline{\boldsymbol{H}}$ - inhabitants per lot; $\boldsymbol{T_{max}}$ – territorial extension reached by the population limit; $\overline{\boldsymbol{O}}$ - municipal occupation by population limit.

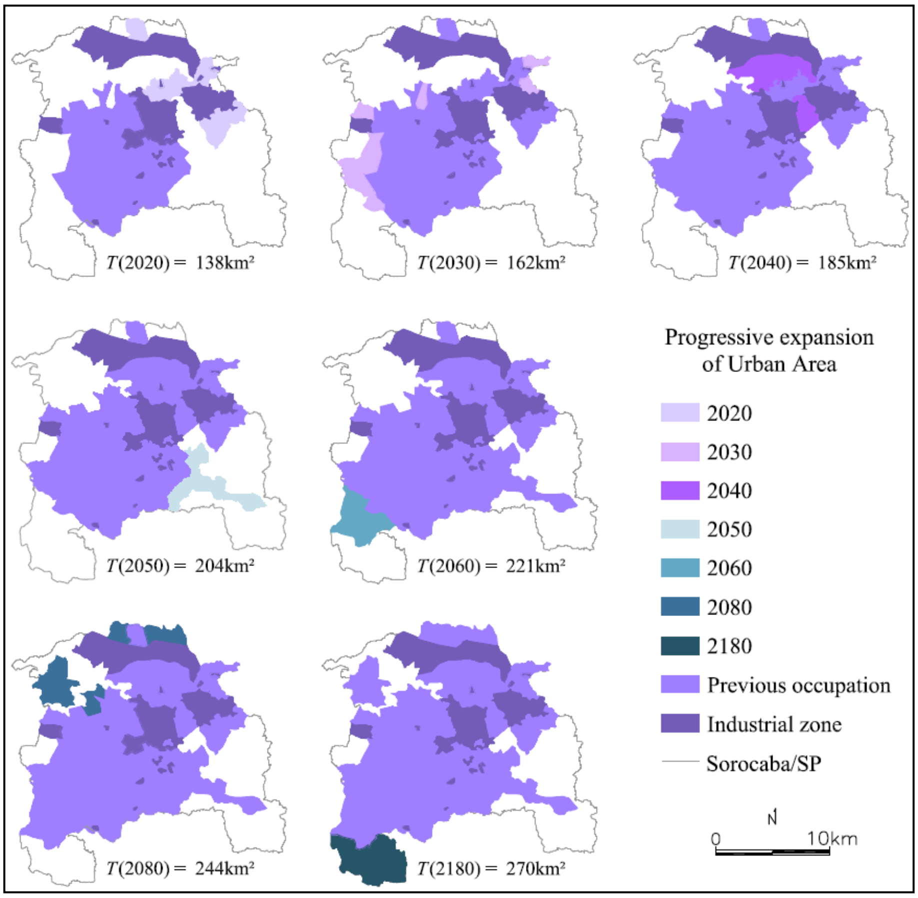


Source: Developed by Authors.

On increasing from 3.3 to 4.0 inhabitants per lot, the urban area would reach a maximum extension (T_{max}) of 404 km², equivalent to 90% of the municipal territory. This value can still be considered excessive, because to maintain the industrial zone, that occupies 14.65% of the territory as established in current law, it would be necessary a greater reduction of the rural zone. To maintain and re-compose the rural zone that has been reduced alarmingly in recent years $\overline{H}$ should be increase to 5.0 inhabitants per lot. In case of $\overline{H}$ reaches 6.0 inhabitants per lot, there will be a reduction of current urban area of 15.4%. In this scenarios ($\overline{H} = 6$), the average population density of Sorocaba city would be approximately 50 inhab. ha^{-1} that can still be considered low. However, in this scenario only 60% of municipal extension would be occupied by urban area, providing a potential increase of 75.5% in rural area, equivalent to 48.9 km², or more areas for industrial expansion. By considering this alternative, a guideline for the sustainable territorial planning of Sorocaba city, according to population dynamics, would be to expand the urban area gradually, as in the simulation presented in Figure 04.

In this simulation were projected urban area increments according to equation (10), which resulted in an average increase of 220 ha per year until 2060. In the following decades began a sharp drop period in population growth rate (Figure 02), accompanied by a reduction in demand for territorial expansion (Figure 03). As the reduction in demand is not linear, but logistic, a further increase of 110 ha per year is proposed for the period 2060-2080 and of 22 ha per year for the period 2080-2180, when the population is expected to stabilize.

Figure 04. Simulation of progressive urban expansion for Sorocaba city: $\boldsymbol{T(t)}$ - urban territorial extension in the year $\boldsymbol{t}$.



Source: Developed by Authors.

In Figure 04, territorial expansions were distributed by considering the connectivity of urban areas and environmental conservation, current use and occupation of land, services and trade corridors, as well as approved allotments according to municipal legislation. However, for reviewing purposes of the municipal Master Plan, such expansions can be performed elsewhere, if more appropriate.

This way, gradual increase in urban areas could prevent irregular spatial growth caused by ground division and occupation of less urbanized, peripheral regions, creating empty spaces and costly implantation of infrastructure and public services. Therefore, the progressive urban expansion, based on the population dynamics model, can represent a more sustainable solution and thus a strategic guideline for the territorial planning and management, mainly in the economic hub of metropolitan regions, as Sorocaba city. Nevertheless, the sustainability of this pattern of expansion implies a regional social pact, to ensure the water and food security of Sorocaba metropolitan region, for which it is necessary to maintain the agricultural profile of Piedade and Porto Feliz cities for the next decades, by means of the payment for environmental services (PES), provided by agriculture, as already successfully occurred in the Brazilian scenario (Zolin et al. 2014). PES is a political tool to face environmental degradation and deforestation, which should be integrated to other activities and actions within a framework of strategic planning of the territory (Perevochtchikova & Oggioni 2014). This tool presents economic, environmental, cultural and social consequences that, in the case of agriculture, empower the rural community against pressures from external stakeholders, such as real estate speculation, reducing the rural exodus; promoting food security; as well as ensuring the maintenance of environmental services provided by farming industry.

CONCLUSIONS

For the foregoing, the simulation of scenarios for urban expansion supported by population dynamics can provide a solution for reaching more sustainable cities, especially at the economic hub of metropolitan regions, such as Sorocaba. Thus, scenarios of progressive expansion through gradual increases in the urban area could prevent spatial growth from occurring in a dispersed way. Hence, strategic guidelines for land management and planning can be implemented, aiming to control land parceling and occupation of areas away from the consolidated zone. Such measures would prevent the creation of empty spaces and costly deployment of infrastructure and public services.

The municipality of Sorocaba has achieved good performance in many areas, both in environmental issues such as urban afforestation and basic sanitation, and economic ones, such as the Human Development Index and the Gross Domestic Product. However, changes in the territorial structure, such as the reduction of soil permeability parameters, of the rural area and the environmental conservation zone tends to aggravate problems related to the suppression of natural areas, as well as the occupation of areas with risk of flooding. Recently, the rural area of Sorocaba has been reduced to less than one-third of that occupied over the last ten years. This reduction intensified the pressure on areas with productive and environmental functions, due to the increase in the occupation rate and waterproofing caused by the urbanization.

In order to prevent disorganized urban sprawl and, consequently, to compromise sanitary conditions, biodiversity, resources and environmental services; as well as the availability of water and agricultural supplies, become important subsidies capable of supporting territorial planning. Through the simulation of scenarios using the proposed approach, it was verified that the urban extension established by the local law is oversized for the current conditions, corroborating with the thesis that the recent expansions may have been influenced by interests of the real estate market.

Based on the projected scenarios, it was also concluded that the maintenance of current guidelines could cause critical consequences, which points to the need for a change in local management, above all, through public policies that induce urban densification. From these simulations, it was possible to design alternative scenarios that favor a higher coefficient of land use, necessary to avoid future crises, even as to enable the reintegration of areas into the rural zone, reversing problems associated with the significant reductions it has been suffering in recent years. In this sense, urban densification and progressive territorial expansion, foreseen in the simulated scenarios, could still provide better efficiency of public investments in infrastructure and services, by saving onerous increases resulting from occupation in areas far from the consolidated urban area. Therefore, the proposed model can be applied in other municipalities, aiming to support strategic decisions, such as progressive urban expansion to prevent disorderly growth.

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Simulação de Cenários Alternativos para Expansão Urbana Apoiada na Dinâmica Populacional: Uma Proposta Metodológica

RESUMO

A expansão urbana implica na redução de áreas de produção rural, assim como aumenta a pressão sobre os espaços naturais. Dessa forma, se não ocorrer de forma criteriosa, a urbanização pode comprometer as condições sanitárias, a biodiversidade, os recursos e os serviços ambientais. O objetivo desse trabalho é apresentar um modelo matemático para expansão urbana com base na dinâmica populacional, o qual foi aplicado como estudo de caso no Polo Econômico da Região Metropolitana de Sorocaba - RMS. Os materiais corresponderam à dados censitários e parâmetros urbanísticos da legislação aplicável. Como resultado, constatou-se que a extensão urbana de Sorocaba está superdimensionada, e que a manutenção das condições e diretrizes vigentes terá consequências críticas, tornando necessária uma mudança na política local. Conclui-se que o modelo proposto pode apoiar decisões estratégicas, prevenindo problemas relacionados ao crescimento desordenado.

Palavras-Chave: Modelagem; Zoneamento; Gestão.

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