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Spatial and Temporal Changes in the Land Use and Cover of the Paraíba Valley in São Paulo, Brazil: Development of Future Scenarios

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A B S T R A C T

The Paraíba Valley in São Paulo, Brazil, is marked by great transformations. The Brazilian economic cycles changed this region and transformed it into a great mosaic of pastures, forest fragments, and urban areas. Temporal studies on land use and cover have given information on these changes and evaluated their impacts. The conversion of extensive areas of the Atlantic Forest into eucalyptus crops is noticeable; this monoculture developed greatly and is expanding steadily in this valley. This land-use conversion has consequences, such as forest fragmentation, and losses in biodiversity, and water and soil quality. Developing future scenarios (2010 to 2050) that simulate changes in land use and cover is essential for an efficient and sustainable public management. Thus, the objective of the present study was to develop future scenarios while considering different social, economic, and environmental issues, based on analyses of the dynamics of forestry expansion in the Paraíba Valley in São Paulo, Brazil. The scenarios developed were classified as Trend, maintaining the same change patterns of the observed period (2000 to 2005); Optimistic, decreasing conversion rates of natural vegetation into forestry and pasture areas; and Pessimist, increasing deforestation rates and increasing eucalyptus and pasture areas. Future scenarios for the period of 2010 to 2050 were developed in the Dinamica Ego software, and it proved to be effective, presenting trends and predispositions of changes in land use. These results can be used for environmental planning focused on sustainability, better management of natural resources, and development of economic activities.

Keywords: Forestry, Silviculture, Dynamic Spatial Modeling, Atlantic Forest

Análise Espaço-Temporal de Mudança de Uso e Cobertura da Terra na Região do Vale do Paraíba Paulista: Desenvolvimento de Cenários Futuros

RESUMO

O Vale do Paraíba paulista é marcado por grandes transformações vinculadas aos ciclos econômicos brasileiros que mudaram a região transformando-a em um grande mosaico de pastos, fragmentos florestais e área urbana. Estudos temporais de uso e cobertura permitem observar essas mudanças e avaliar os impactos gerados por elas. É notória a substituição de extensas áreas de Mata Atlântica para o monocultivo de eucaliptos que possui alto desenvolvimento e constante expansão no Vale. Tal conversão de uso traz consequências como a fragmentação florestal, perda de biodiversidade, da qualidade das águas e do solo. A possibilidade de desenvolver cenários de simulação de mudanças de uso e cobertura da terra é fundamental para uma gestão pública eficiente e sustentável. Visando essas questões o presente estudo busca projetar cenários futuros levando em consideração diferentes questões sociais, econômicas e ambientais, a partir de análises sobre a dinâmica de expansão da silvicultura no Vale do Paraíba paulista. Os cenários criados podem ser classificados como "Tendencial" que mantém os mesmos padrões de mudanças do período observado (2000-2005); "Otimista" que diminui as taxas de conversão para silvicultura e pastagem, aumentando as áreas vegetadas; e "Pessimista" que alavanca as taxas de desmatamento a partir do crescimento dos cultivos de eucaliptos e pastagem. O desenvolvimento de cenários futuros de 2010 a 2050 no DinamicaEgo se mostrou eficaz, apresentando tendências e pré-disposições de transições de uso do solo sendo possível a utilização dos resultados no planejamento ambiental visando à sustentabilidade e melhor gestão dos recursos naturais e desenvolvimento de atividades econômicas.

Palavras-chave: Silvicultura, Modelagem Espacial Dinâmica, Mata Atlântica

Introduction

Population growth and economic development have transformed landscapes worldwide for decades, and the intensification of some processes, especially those linked to economic growth, causes significant changes in land use (Silva et al., 2017). Studies on these changes have been increased, with important results for guiding environmental management and promoting strategies for adequate economic development focused on preserving the environment, contributing to the elaboration of public policies, and supporting decision making on these issues (Almeida, 2003; Silva et al., 2012; Pavanelli et al., 2014).

The Paraíba Valley in the state of São Paulo, Brazil, has a history of expressive landscape changes, mainly because of the proximity of this region to two great Brazilian cities—Rio de Janeiro and São Paulo. This proximity is strategic for productive sectors, which increased their activities in this region (Arruda, 2010).

Currently, the Paraíba Valley has one of the highest concentrations of eucalyptus crops in Brazil (IBGE, 2014). Fiscal incentive policies started in 1965 (Freitas Junior et al., 2012) were an important factor for the development of the Brazilian industry, increasing the wood supply, benefiting cellulose and paper industries (Tuoto and Hoeflich, 2008). According to Freitas Junior and Marson (2009), this process was based on technical, scientific, financial, and legal investments that favored the development and consolidation of the eucalyptus production sector. On average, 92.4% of the wood logs produced between 1990 and 2015 was intended to cellulose and paper production, denoting the performance of this sector in the region and its importance for the regional economy. The performance of this sector crossed regional boundaries; the Brazilian wood production increased from 32 million m3 in 1990 to 74 million m3 in 2012 (Marques, 2015). Thus, identifying and analyzing these areas is important for territorial management, especially for the conservation of the Atlantic Forest, which is a highly degraded biome due to the Brazilian economic cycles. Eucalyptus plantations in large areas of this region have caused significant land-use conversions; 55% of the forestry area in 2010 was developed over pastures, 15% over secondary vegetation, 9% over gallery forests, and 7% over clear fields (Carriello and Vicens, 2011). The effects of this monoculture on the biodiversity are noticeable, since this activity caused fragmentation of the forest and elimination of ecological corridors, hindering the genetic flow of fauna and flora.

Eucalyptus trees require greater amount of water during their growth phase (Rodrigues et al., 2015), from 6 to 8 years of age, when cuts for the homogenization of the planting cycle are made (Carriello and Vicens, 2011). This can cause changes in the hydrological cycles of the basin. The presence of vegetation cover is important for hydrological processes, especially regarding the variations of infiltration and runoff rates. The intense human action during several economic cycles on the Paraíba Valley region resulted in an intense deforestation, forming a complex mosaic consisted of pastures, forest fragments, and urban areas (Camarinha et al., 2011).

Multitemporal studies on land use and cover changes make possible the observation, detection, mapping, and quantification of changes occurring in a region throughout the years. Marchesan et al. (2013) evaluated land use and cover in Faxinal do Soturno RS, Brazil, throughout 25 years and observed an increase in natural forest areas due to the regeneration of areas previously occupied by agriculture. Fernandes et al. (2015) studied changes in land use and cover, and forested areas in the semi-arid region of Sergipe, Brazil and found a reduction in forest regeneration from 2003 to 2013, with greater effects on the caatinga vegetation, which was mostly converted into pastures. These studies were made using geoprocessing and remote sensing techniques, which are great tools for environmental monitoring. The improvement of these tools made possible to analyze past and present situations, and simulate future scenarios of an area for the next few years while considering environmental and socioeconomic aspects.

The development of future scenarios considering factors that affect the physical and socioeconomic regional dynamics makes possible the simulation of land use and cover conditions representing the space in the long term; this simulation assists on decision making for the mitigation of environmental impacts, economic ecological zoning, and urban management (Almeida et al, 2005). Simulation and prognoses models for changes in urban areas were developed by Almeida et al. (2005) as an instrument for subsidize urban public policies and actions.

The models known as LUCC (Land Use Cover and Change) show an approximate representation of the actual space, indicating predispositions for changes. These models have limitations of use due to the complexity in the modeling process; they do not predict where and when the landscape will be altered due to extreme events, and economic crises, for example. Thus, these models indicate a future trend of changes that may or may not occur.

Considering the importance of this subject, the objective of the present study was to develop future scenarios of changes in land use and cover for the Paraíba Valley region, in the state of São Paulo, Brazil, with emphasis on eucalyptus crops, presenting estimated scenarios for this region up to 2050. The forestry, natural vegetation, and pasture classes were considered for the modeling.

The scenarios were developed in the software Dinamica Ego, according to the methodology proposed by Soares-Filho et al. (2009). The models were based on cellular automata to a better understanding of the causal mechanisms, and processes of development of the environmental systems, and determination of the status and evolution of these systems under different socioeconomic, political, and environmental scenarios (Rodrigues et al., 2007). These scenarios will contribute to the anticipation of public actions in the occurrence of the predicted phenomena, such as changes in land use and cover (Ximenes et al., 2008), and increasing efficiency in territorial and environmental planning and management.

Material and methods

Simulation Model of Land Use Changes

Simulation models of changes in the landscape can be used to quantify conversions of land use and cover throughout a period, and investigate the effects of variables linked to these conversions (Kawashima et al., 2015), identifying change patterns and their impacts on the environment. Future projections can estimate trends of changes based on the development of future physical and socioeconomic scenarios.

Projecting future scenarios requires prior information on the regional dynamics that can be acquired from spatial analysis of maps of land use and cover. Thus, maps of land use and cover of 2000 to 2005 (Neves et al., 2013) were crossed to identify changes. This period was chosen for the validation of the landscape to be simulated for 2010, because of the availability of the actual map for this year.

Calibration

The calibration process affects directly the results of the simulations; it selects the best set of variables that explain the land use and cover changes occurring in a period (Delaneze, 2011) to produce the best fit of the empirical data to the observed reality (Almeida, 2003).

The changes occurring in the period 2000-2005 were observed, and conversion matrices were calculated, which accounted for the percentage of changes that occurred in this period. These percentages represent the total net rates of changes by the single-step matrix, and the annual rates of changes by the multi-step matrix.

The development of models requires the identification of inductive agents of the conversions. The search for these agents focused on variables capable of affecting the eucalyptus cultivation, considering physical, social, and economic aspects. These variables (Table 1) can be classified as dynamics, when they change over time; static, when they remain fixed, without changes throughout the modeling process; and restrictive, according to their function. These variables will affect positively or negatively the expansion of the eucalyptus areas in the developed models.

Input maps must be systematized for the correct functioning of the simulation model; these maps must be in matrix format and have the same projection/data and same number of rows and columns, since the changes are analyzed pixel by pixel.

The development of the spatial dynamic model requires data for calibration, and election of the best variables to be maintained in each data set. The weights of the evidence, based on the probability of occurrence of a conversion due to previous events, contribute for the selection and analysis of variables that affect these conversions. Positive weights favor the conversions, negative ones prevent them, and values close to zero have little or no effects on them.

The weight of evidence method (Goodacre et al., 1993; Bonham-Carter, 1994; Soares-Filho et al., 2009) was applied to develop a conversion probability map that represents the most favorable areas for changes (Soares-Filho et al., 2002). This method is based on the Bayesian probability theorem and determines the probability of an event to occur, based on the previous occurrence of an evidence (Benedetti, 2010). Thus, the weights of evidence represent each effect on a variable in the spatial probability of a conversion (Soares-Filho et al., 2009).

Table 1. Description of the variables used in the modeling process

Variable	Explanation	Source
Altitude	The difference in height from sea level. Temperature decreases with increasing altitude; this may or may not benefit crops.	Digital Elevation Model - SRTM - Resolution: 90 m
Declivity	Areas with higher slopes have high runoff capacity, which are responsible for erosion (Crepani et al., 2001). It causes instability in the terrain, characterizing these areas as very vulnerable, especially when deforested.	Digital Elevation Model - SRTM - Resolution: 90 m
Hydrography	Proximity to rivers is beneficial for industries, but harmful to the environment because of losses in local water quality and availability.	Continuous Cartographic Base of Brazil - IBGE
Highways	Positive variable to the expansion of crops; it increases the flow of production, reduces costs and makes the plant extraction and production economically viable.	Continuous Cartographic Base of Brazil - IBGE
Types of Soil	Soils with low thickness, such as Cambisols (Inceptsols) were ideal for implementation of forestry in the region during the last decades (Camarinha et al., 2011)	AMBDATA - INPE
Conservation units	Restrictive agents to the expansion of eucalyptus crops; they are divided into different stages of preservation; thus, their degree of restriction will vary according to each category.	Ministry of the Environment
Permanent preservation areas	These areas are directly related to environmental functions; thus, they are restrictive areas; their irregular occupation may lead to the loss of their functions.	Delimited from the Digital Elevation Model SRTM - Resolution: 90 m
Vegetation	Much of the plant cover of the Paraíba Valley has been converted for diverse types of use. Landscape changes are significant on these spaces that have undeniable environmental functions.	Ministry of the Environment

The calibration process is ended with the correlation analysis of the maps. This process identifies variables capable of explaining the changes; thus, the variables must be spatially independent. Statistical tests—Crammer Coefficient (V) and Uncertainty Index of Joint Information (U)—were applied to the pairs of variables. They range from 0 to 1; a cut-off of 0.5 was set to identify the association level of the variables; values smaller than 0.5 indicate less spatial association (Bonham-Carter, 1994; Almeida, 2003). According to Soares-Filho et al. (2009), variables presenting higher association than expected must be removed to avoid forcing the model, and to identify more clearly the variables responsible for each conversion. Therefore, this calculation identifies variables that must remain in the model due to their high association or spatial dependence (Benedetti, 2010).

Validation

The validation of the model starts with the identification of spatial patterns between the simulated landscape map and the actual landscape map for the same year. Spatial models require a neighborhood comparison of the cells, since they may not show cell-to-cell similarity and have similar patterns (SoaresFilho et al., 2009).

According to by Benedetti (2010), the validation process of the model in the Dinamica Ego is given by the application of constant decay and exponential decay functions on the difference maps. These maps show the observed changes (initial map - final map) and simulated changes (initial map - simulated map). Hagen (2003) developed new metrics with the fuzzy similarity that considers the uncertainty of the location of a category within the neighborhood of a cell. This method was modified in the Dinamica Ego by Soares-Filho et al. (2009) to employ an exponential decay function with the distance to consider the distribution of the cell around a central cell. These authors presented another method to measure spatial adjustment through similarity indexes by multiple windows, applying a constant decay function within a variable window size. Finally, similarity maps are generated; these maps show the errors and correctness obtained in the simulation, and the similarity indexes calculated by multiple windows that range from 1x1 to 11x11 (Figure 1).

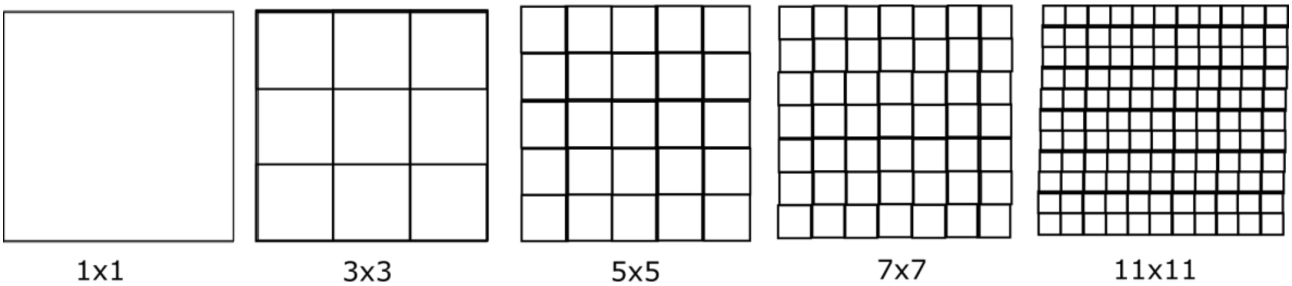

Figure 1. Example of multiple windows used to calculate similarity

Simulation

Simulation models are applied to estimate and develop different social, environmental, and economic scenarios with long-term perspectives. They create future scenarios by determining the annual conversion rates, final use map (2005), weights of evidence, and variables, allocating the percentages that are intended to the expansion and formation of new patches for each conversion, and defining the mean and variance of the size of the patches and their isometry.

The mean size and variance of the patches were established with same parameters for all scenarios. These values were calculated in a Geographic Information System (GIS), crossing the classes of the years 2000 and 2005 to identify the conversions that enabled the calculation of the size of the patches. The isometry value varies from 0 to 2 and is connected to the structural form of the patches (fragmented or not); this value was 1 for all conversions.

Simulation maps of annual changes were developed for the period 2010 to 2050 with three different scenarios due to the approaches and environmental perspectives.

1. Trend scenario: The demand for the eucalyptus crop will continue to expand as in the period between 2000 and 2005;
2. Pessimist scenario: Overheating of the economy, increasing the demand for cellulose and paper. This will enable a rapid increase in eucalyptus crops, increasing deforestation rates, agricultural activities, and pasture areas;
3. Optimistic scenario: Weakening of the productive sector, increased inspection in conservation units and permanent preservation areas, restricting deforestation and promoting high rates of forest regeneration, slowing the forestry expansion.

Trend Scenario

The trend scenario is characterized by the maintenance of the trend observed in the period from 2000 to 2005, with expansion of areas with eucalyptus crops, growth of natural vegetation areas, and reduction of pasture areas. A greater value to determine the percentages for expansion and formation of new patches was established to expand the existing patches.

Pessimistic Scenario

This scenario presupposes the overheating of the economy in the industrial sector by the increase of the cellulose and paper industries, thus increasing the areas with eucalyptus crops, and deforestation rates because of the expansion of pastures and forestry. The model disregarded the restrictive variables to build this scenario, enabling the development of activities in conservation units and permanent preservation areas. Higher values for the formation of new patches were defined for the conversions that resulted in forestry areas, and conversion of natural vegetation into pastures, and lower values were defined for the conversions that resulted in natural vegetation areas, and conversion of forestry areas into pastures, thus enabling the total expansion of the pre-existing areas.

Optimistic Scenario

This scenario is based on the consolidation of a more adequate environmental management, with greater governmental oversight, compliance with the laws, restriction of development of forestry on the conservation units and permanent preservation areas, and decrease of expansion of eucalyptus crops, especially over natural vegetation. Thus, 40% of the conversion of pastures into natural vegetation and 50% of the conversion of forestry into natural vegetation areas were assign for the formation of patches; this reduced the total pasture and forestry areas, since these conversions occurred only from the expansion of the existing patches.

Results and Discussion

Calibration

The crossing of classifications of land use and cover in 2000 and 2005 showed 37 conversions occurring during this period. This result indicates that this region is dynamic due to the different land uses for the development of economic activities and others interests. The modeling of each conversion is complex due to their interactions. Thus, the modeling generated six conversions of land use to meet the objectives proposed in the present study; these conversions are the most relevant, involving the interactions between the pasture, natural vegetation, and forestry classes. The percentages of changes, calculated using the multi-step conversion matrix that accounted for the annual rates, showed that 13% of the forestry area is converted into natural vegetation, and 0.8% of the forest areas is converted into eucalyptus crop area annually. Approximately 3.8% of natural vegetation are converted into pasture and forestry areas annually; this characterizes a great forest regeneration. However, forests are not suppressed only by pastures and forestry; other activities linked to agriculture and urbanization contribute to the increased deforestation rates. The pasture areas increase 5.4% and lose around 4.6% of their area annually. This loss can be explained by the conversion of pastures into agricultural areas, urbanization, and recovery of forest remnants. Forestry areas increases 1.4% per year, totaling 7% of expansion over natural vegetation and pastures in this five-year period.

Regarding the weights of evidence for the different variables in the conversion of pastures into forestry, and natural vegetation into forestry areas, the conservation units favor the first, and the latter is avoided in the integral protection units, restricting the development of eucalyptus crops. Areas with smooth-wavy (3% to 8%) and corrugated (8% to 20%) relief benefit the growth of forestry over pasture and natural vegetation areas, since they allow machinery access for the development of this activity. Eucalyptus crops tend to expand in areas with altitudes of 600 meters to 1,200 meters.

Since the variables must be spatially independent, statistical tests capable of dimensioning the dependence degree were applied to the pairs of variables for each conversion. Some variables presented correlation values above 0.5, however, high correlations were obtained only in the Crammer (U) test, thus the variables were kept in the system.

Validation

The validation of the model consisted in comparing the actual with the simulated landscape, thus evaluating how close to the observed reality the model can reach. The probability maps (Figure 2) indicated the more propitious areas to be converted into another class. The model generated a probability map for each interaction, since the changes vary over the years and alter the conversion probability. These maps indicate a range of probability of change of 0 to 1; the closer to 1 the greater the probability of change.

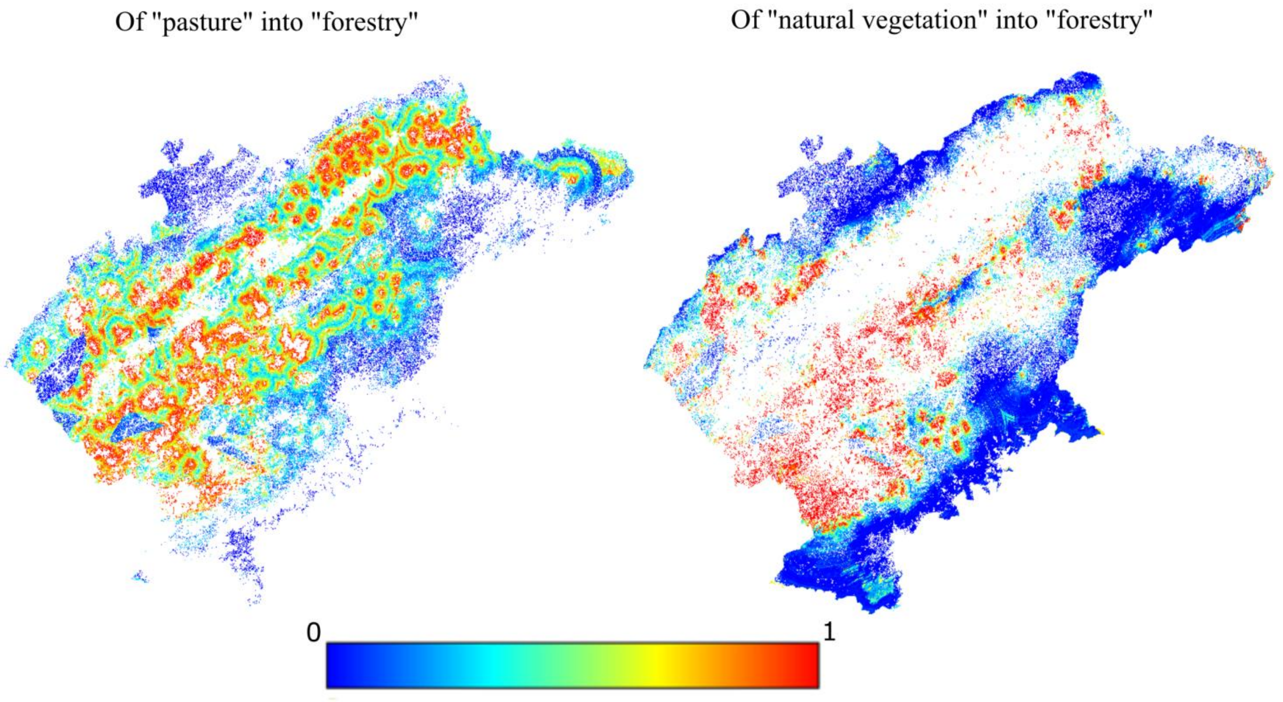

Figure 2. Probability maps of the conversions of pasture into forestry, and natural vegetation into forestry areas

The reference and simulated maps for 2005 (Figure 3) show that the simulated landscape is very close to the actual one, although it presents sparser vegetation cover and increased agricultural area. Based on the results found in the simulation, the forestry area present 2,375 ha less in the simulated map, while pastures and natural vegetation had losses of 23,876 ha and 9,428 ha, respectively.

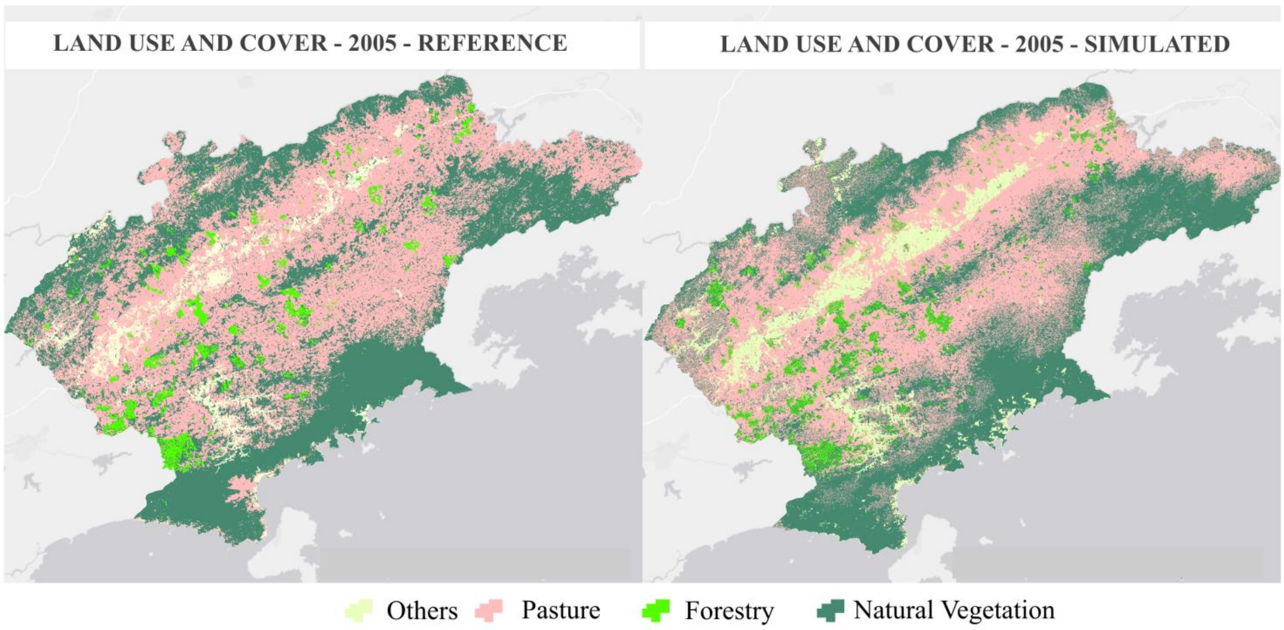

Figure 3. Reference and simulated landscape maps for the year 2005

The similarity indexes (Figure 4) were used to quantify the results of the evaluation as a function of the variation of the sample window size. The minimum similarity indexes in the 7x7 window were greater than 50%, while maximum similarity values equal to or greater than 50% were obtained in the 5x5 window. In general, the increase in windows increases the similarity index, thus, in the window 11x11 the similarity of the maps was 58% to 63.5%.

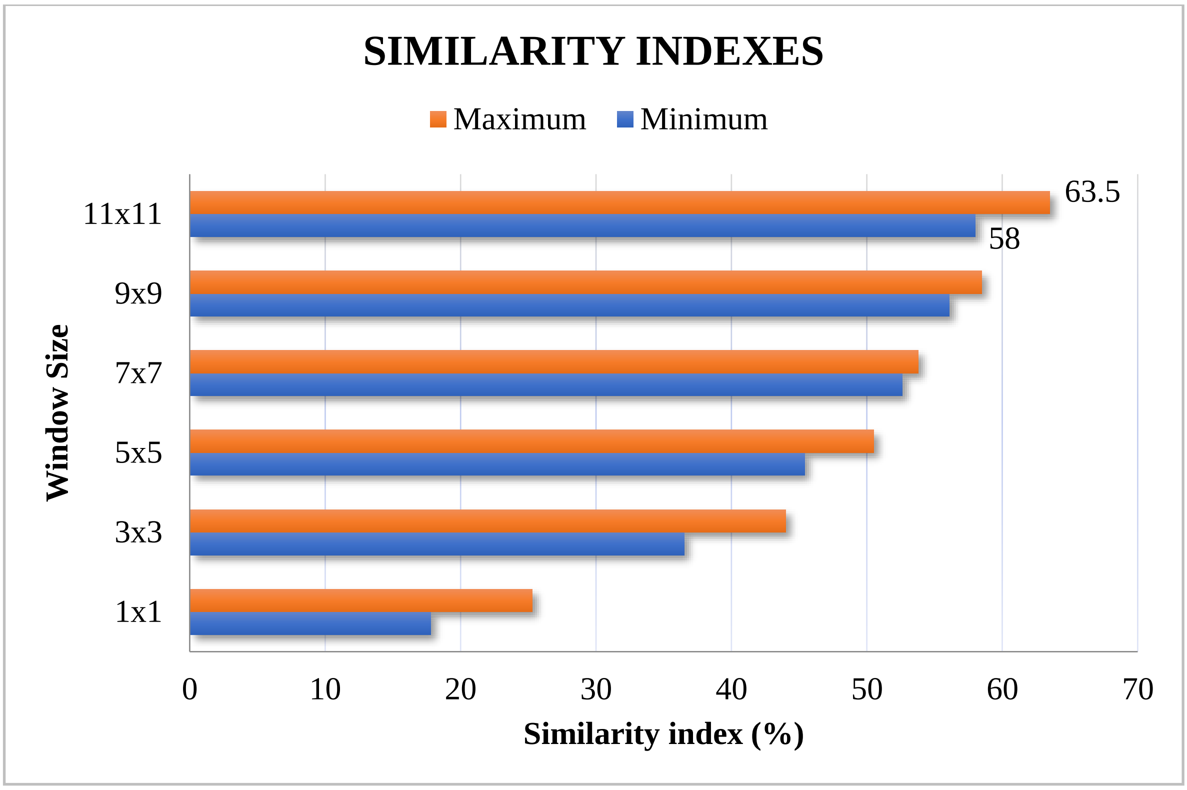

Figure 4. Minimum and maximum similarity indexes in percentages

Piontekowski (2014) simulated deforestation in Rondônia based on rates of 2009 to 2011 and found a similarity of 75% in the 11x11 window. Barni (2009) found 54.7% of similarity in maps for the simulation of deforestation in Roraima, and affirmed that values above 50% are considered satisfactory for the validation of the model when the patterns of spatial distribution of the maps are similar. Ximenes et al., (2008) found 87% to 90% similarity in multiple windows used to validate their model on deforestation in the Amazon. Benedetti (2010) validate dynamic models of changes in forest cover for different regions and periods with 73% to 80% of similarity.

The similarity results were considered satisfactory to meet the objectives of the study, given the complexity of modeling all the socioeconomic, political, and environmental interactions that occur in the region and in assign change-inducing agents.

Simulation

The simulations were used to understand the spatial trends of changes between pasture, forestry, and natural vegetation areas up to the year 2050. Different prognoses have been developed to model economic and environmental issues. Thus, maps describing the annual process of land use changes and land cover, which can be used in the management of the region, were obtained.

Trend Scenario

The observation of changes from 2000 to 2005 showed a growth in forestry and natural vegetation areas, thus pasture areas will reduce over the years. The models named as Trend scenario are characterized by maintaining these same patterns of changes (Figure 5).

Eucalyptus plantations are distributed in different microregions of the Paraíba Valley, in the state of São Paulo, Brazil. The scenarios make their conversion into natural vegetation more evident. Large properties located southwest of this region are reducing and will be almost extinct within these 40 simulated years. Small patches are also presenting this type of conversion throughout the study area.

There is a trend in this scenario for eucalyptus crops to expand and migrate almost entirely to the north of the Valley. This region is characterized as a lowland area with altitudes of 200 to 600 meters, with high altitudes, relief varying from soft-wavy to wavy, and high density of highways, which benefits this crop due to the rapid connection and distribution of the production to other regions. Moreover, restrictive variables such as conservation units are non-existent in this region.

These scenarios maintain a trend of what was observed in the actual thematic maps; thus, the simulated and reference map of 2010 could be compared. The simulated forestry area presented satisfactory results when compared to the actual area, since a difference of only 157 ha between the maps for this year was observed, however, only 23% of the 60,694 ha of simulated crop are superimposed spatially, i.e., the parameters used and the effect of the explanatory variables created new forestry patches in different locations than the ones in the reference map.

The shape of the simulated forest patches based on the isometry values was less fragmented, however, the actual patches of eucalyptus crops in 2010 were sparse; it could not be modeled considering the results. However, the proportionality showing a pasture area larger than natural vegetation was maintained. Regarding the spatialization, the simulated and actual natural vegetation and pasture areas presented superimposition of 74% and 72.9%, respectively. These areas were increased from the reference map, with increase estimates of 7.4% and 6.6% for pasture and natural vegetation areas, respectively.

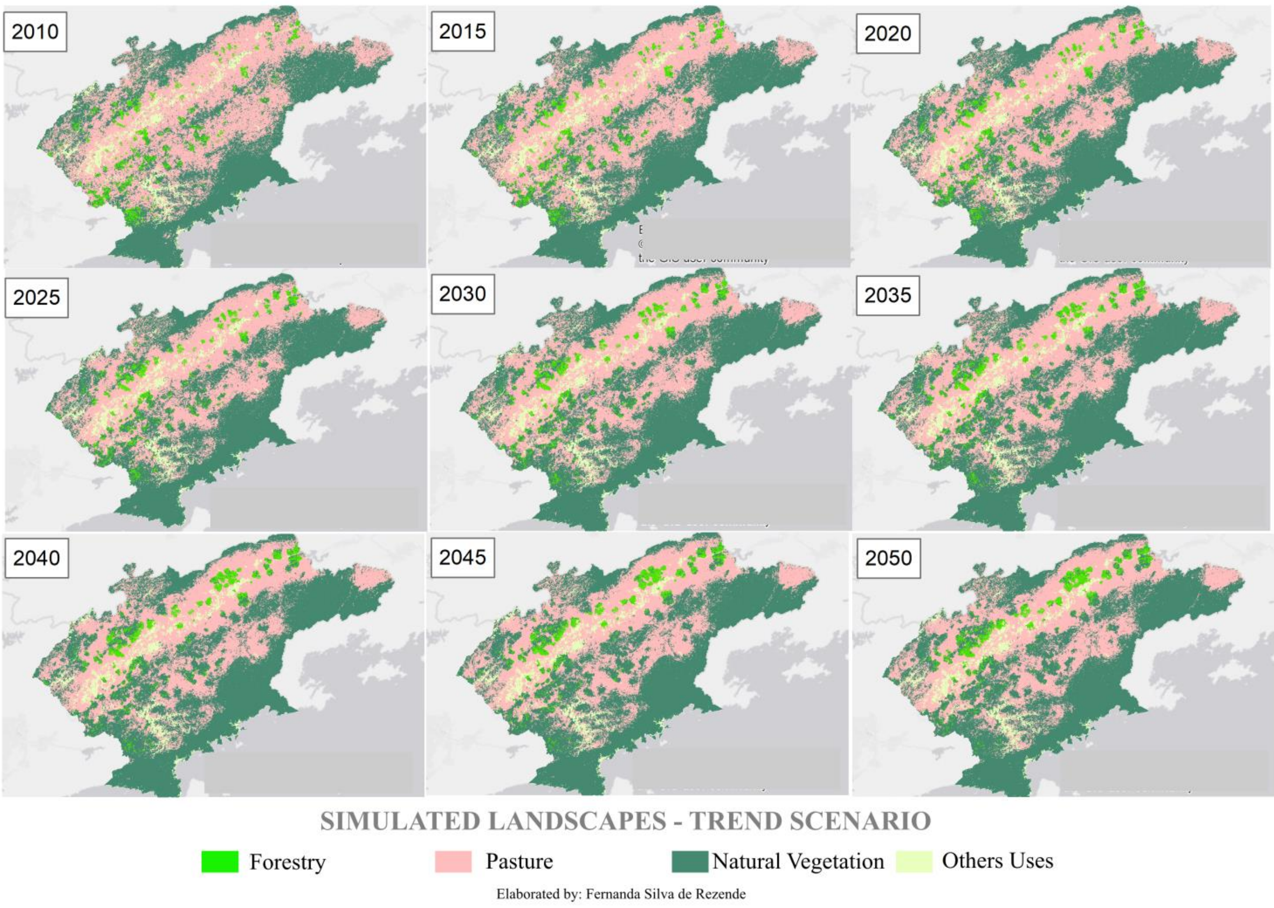

Figure 5. Simulated landscapes of the Trend scenario for the region of the Paraíba Valley in the state of São Paulo, Brazil, in 2010 to 2050 with five-year periods

Pessimistic Scenario

The increasing deforestation and consequent forest fragmentation caused by the multiple regional land uses, especially eucalyptus crops and extensive livestock areas can cause numerous and significant changes in the landscape, transforming all local dynamics, and impact the environment.

The increase in forest fragmentation is a negative factor; it alters local environmental conditions and causes the edge effect, which potentiates the invasion of opportunistic and exotic species of fauna and flora into these environments, increases the competition between species, and threatens the biodiversity. According to Arruda and Sá (2003), the edge effect favors the establishment of generalist species that migrate to the edges of forest fragments; this species present high dispersion and, eventually, they penetrate the central areas of these fragments.

Pessimistic prognoses for the Paraíba Valley were developed based on these issues. The conversion that result in natural vegetation were reduced to its lower growth, and conversion increasing forestry and pasture areas were increased.

These estimates made possible to create an environmentally unfavorable scenario for the region, however, the economic growth of eucalyptus crops is positive for the regional economy, mainly for the paper and cellulose industries.

In the pessimistic scenario (Figure 6), the forestry patches remained well distributed throughout the Paraíba Valley, not concentrating only in areas of the north as in the other scenarios. The natural vegetation tended to be converted into pastures, thus showing a significant increase of these areas in the Mantiqueira Mountains, which maintain great forest fragments preserved.

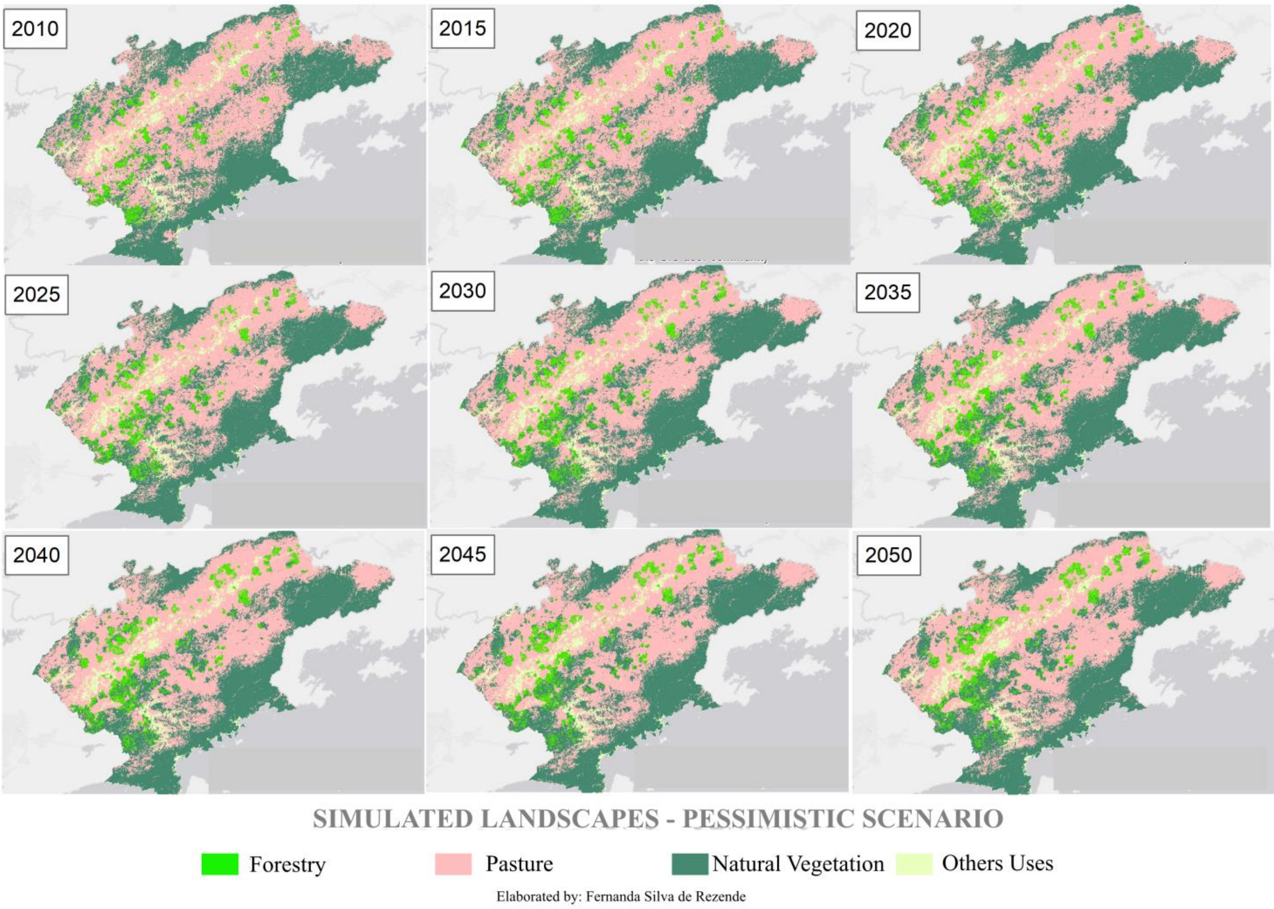

Figure 6. Simulated landscapes of the Pessimistic scenario for the region of the Paraíba Valley in the state of São Paulo, Brazil, in 2010 to 2050 with five-year periods

Optimistic Scenario

A decrease in deforestation rates and slow growth of pasture and forestry areas are expected in the optimistic scenario. Based on economic and political aspects, the optimistic scenario seeks to propose a greater control over the restrictive areas, such as conservation units and permanent preservation areas, thus restricting the use of these areas for eucalyptus crops and pastures. Thus, changes in the weights of evidence were made, considering very negative values, decreasing the probability of change.

The percentages of conversions were obtained from changes made in the conversion matrix calculated by the model in the calibration process. Thus, the conversions of pasture into forestry, natural vegetation into forestry, and natural vegetation into pasture areas decreased 0.5%, 1.5%, and 2%, respectively. Considering a greater growth of areas with eucalyptus, the conversion of forestry into pasture, pasture into natural vegetation, and forestry into natural vegetation areas had increases of 0.5%, 2%, and 1.5%, respectively.

The simulated maps (Figure 7) show a trend of migration of the forestry areas to the north of the region due to the factors mentioned. This migration is positive for this scenario since this region is composed mainly of pastures, thus reducing the pressure and suppression of the natural vegetation.

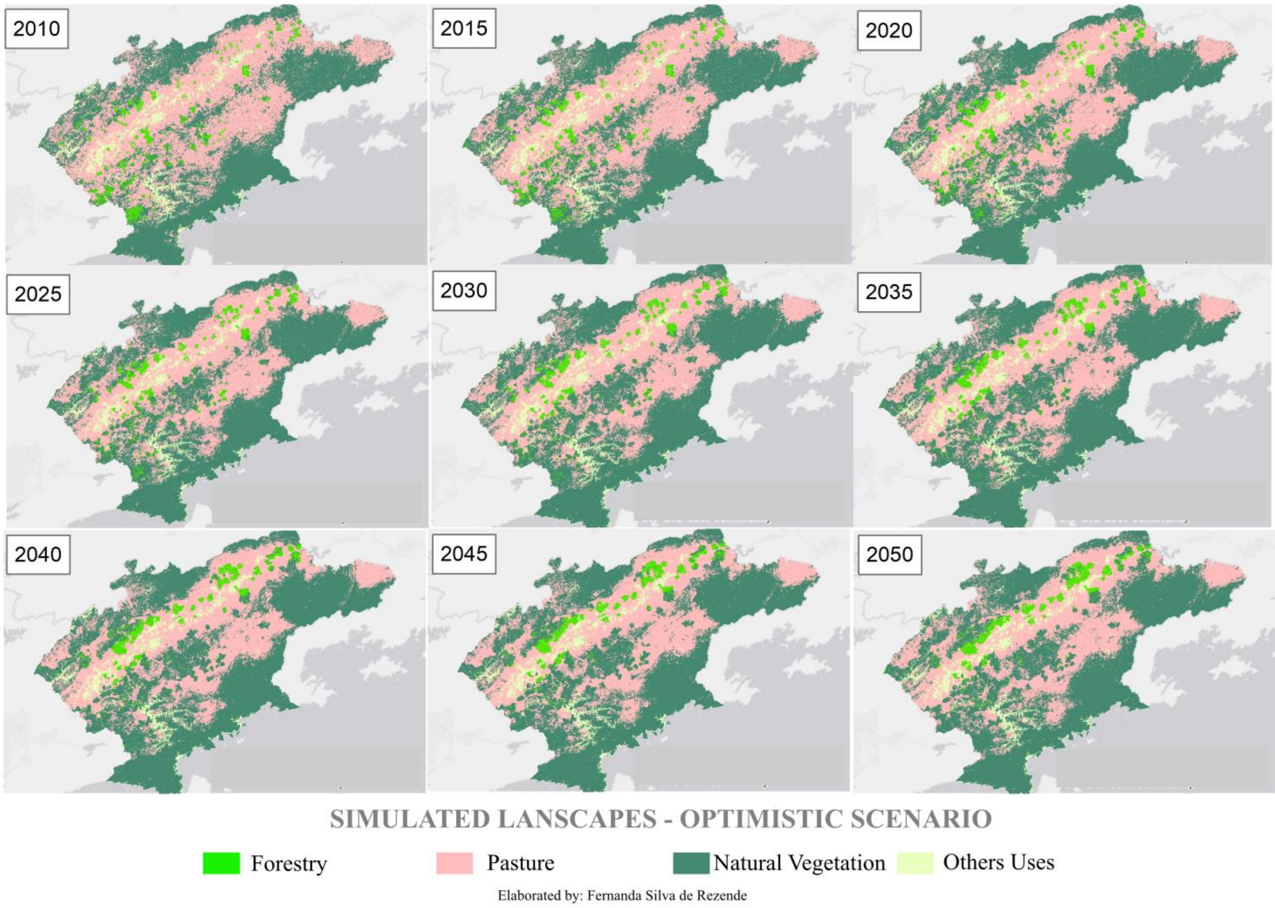

Figure 7. Simulated landscapes of the Optimistic scenario for the region of the Paraíba Valley in the state of São Paulo, Brazil, in 2010 to 2050 with five-year periods

Course of Simulated Classes

Forestry

In the Trend scenario, eucalyptus crops lost large areas to natural vegetation, slowing its accelerated growth in the region and affecting the regeneration rates of the natural vegetation cover. This loss can be explained by the natural regeneration of the forests and areas left without crops. Despite this tendency, this monoculture increased in the first ten years in approximately 2,600 ha, however, it showed small expansions from 2025, reaching 64,610 ha in 2050.

In the Pessimistic scenario eucalyptus crops start with 77,134 ha in 2010, which is a larger area than they reached in 2050 in the Trend scenario. This crop had an accelerated growth, mainly in the first 15 years; forestry areas increased over 25,000 ha from 2010 to 2025. This value is almost 9-fold the expansion found in the 40-year period in the first scenario. In the last simulated year, the eucalyptus crop reached 105,463 ha.

Contrastingly, the Optimistic scenario was like the Trend scenario regarding the forestry class, presenting more than 58,000 ha of eucalyptus in 2010, with significant expansions up to 2025, reaching around 61,000 ha. However, these expansions slowed in the following years, presenting 61,862 ha in 2050. This result is 43,783 ha, and 2,748 ha lower than those found in the Pessimistic and Trend scenarios, respectively. The trends for the forestry areas in the different scenarios is shown in Figure 8.

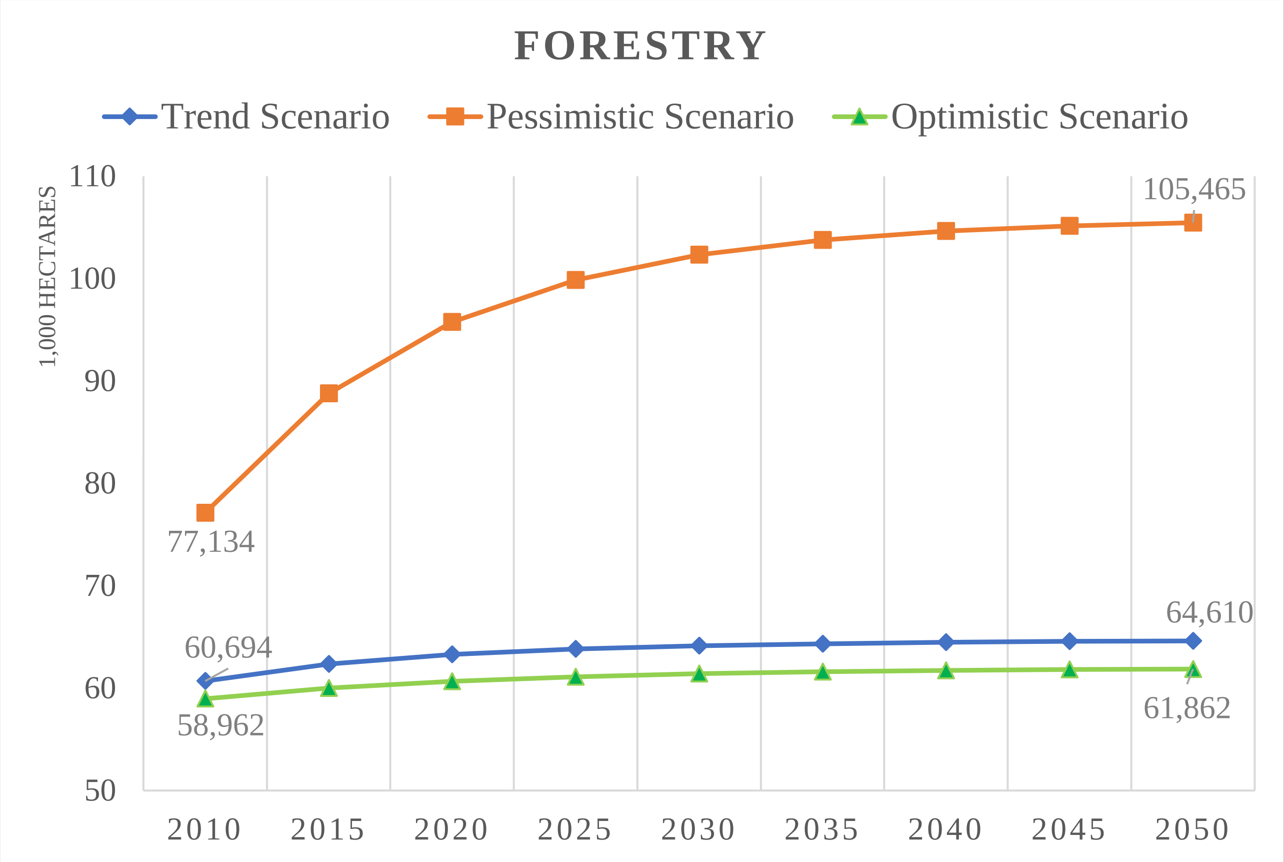

Figure 8. Trends of the Forestry Class in the different scenarios developed

Natural Vegetation

The natural vegetation areas presented high regeneration capacity over pasture and eucalyptus areas, with growth of over 110,000 ha in the Trend scenario. The first 15 years show a trend of rapid growth (approximately 86,000 ha) compared to the other periods, which had a growth of approximately 30,000 ha. The growth of areas of natural vegetation is beneficial to the region from the socioenvironmental point of view, and essential for biodiversity preservation and conservation of water resources.

The changes in this class (Figure 9) were not linearly in the Pessimistic scenario; it decreased between 2010 and 2030 as expected, from 631,447 ha to 623,083 ha, but increased from 2035, reaching 623,394 ha in 2050, thus presenting 191,758 ha less than area in the Trend scenario.

The natural vegetation areas in the Optimistic scenario increased in all simulated years, reaching 845,266 ha in 2050, which is a higher value than those of the other scenarios. This class had a growth of 131,000 ha throughout the 40 simulated years, and contributed to the reduction of deforestation rates.

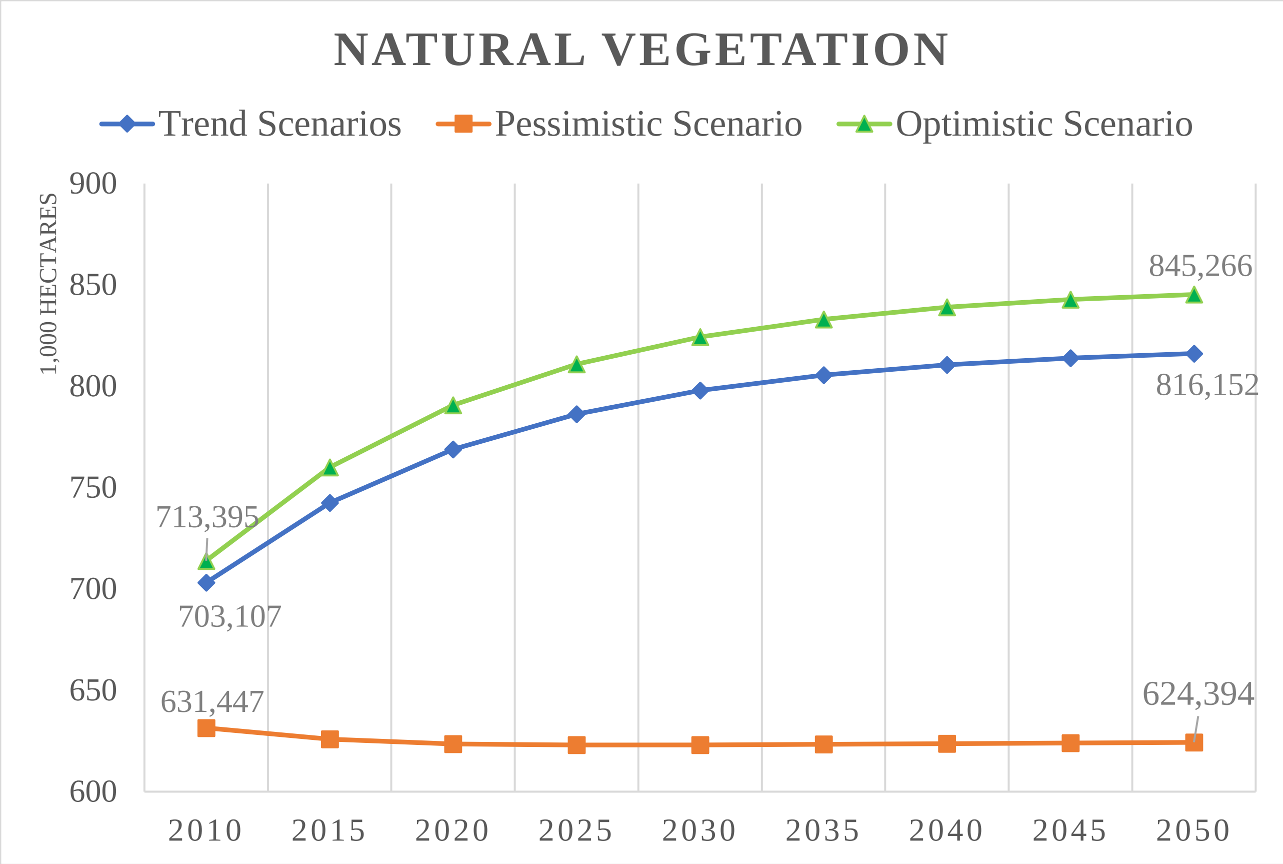

Figure 9. Trends of the Natural Vegetation Class in the different scenarios developed

Pastures

The pastures tended to lose areas in all scenarios throughout the simulated years. These decreases reached 117,000 ha in the Trend scenario in 40 years, with a significant decrease in the first 10 years. The pastures areas reduced by 21,358 ha in the Pessimistic scenario, even with the attribution of values that would favor their growth. However, this reduction is minimal compared to the other scenarios; the pasture area in the pessimistic scenario was 785,530 ha and in the Trend scenario it was 730,337 ha in the year of 2010. Moreover, despite this constant decrease, these areas remained predominant in the region until 2050, when they reached 764,191 ha, and 150,000 ha more than in its area in the Trend scenario. Pastures and natural vegetation areas were similar in the Optimistic scenario in 2010, but the natural vegetation area expanded and pastures lost more than 134,000 ha in the following years, this decrease was 5-fold the observed in the Pessimistic scenario.

The trends for the pasture areas in the different scenarios is shown in Figure 10.

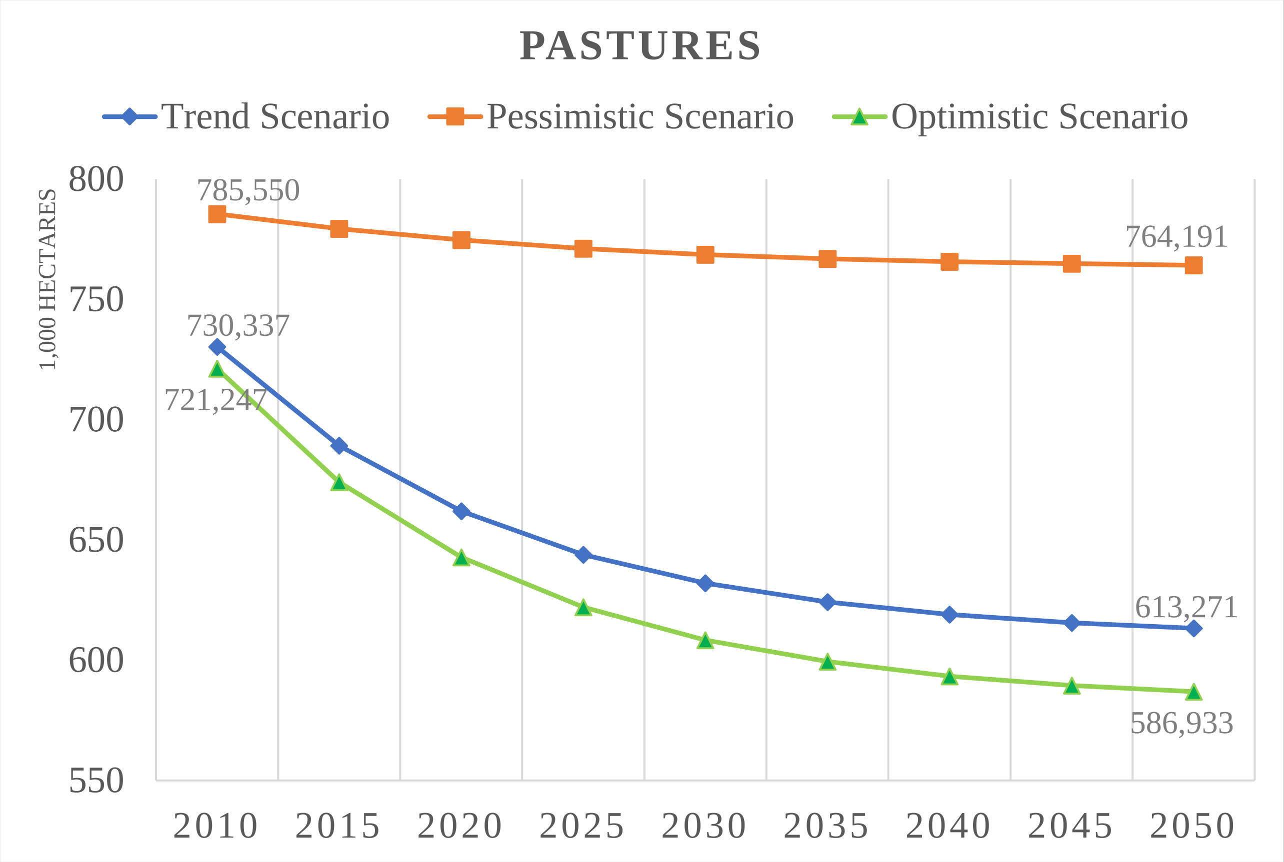

Figure 10. Trends of the Pastures Class in the different scenarios developed

Conclusion

This study evaluated the dynamics of land use and cover in the region of the Paraíba Valley in the state of São Paulo, Brazil, and showed the strong effect of the economic sectors on the constant changes of the original landscape, denoting the expansion of eucalyptus plantations.

The thematic maps on temporal series of land use and cover showed estimated future landscapes for this region based on the changes observed between 2000 and 2005, building several environmental scenarios, considering physical, social, political, and economic aspects.

Simulation of future landscapes with wide temporality requires careful analysis, since it represent trends, and certain environmental issues and changes capable of causing significant environmental changes along the years are not possible to predict. Thus, the modeling has limitations, depending on the approximation of the representation of the actual space, and the complexity of the model linked to the predictability of events and economic crises, for example.

These results point out predispositions for environmental changes, thus, they can be used in public management as a reference for economic-ecological zoning, and assist in the implementation of public policies, fiscal incentives, territorial planning, and management and use of natural resources.

The scenarios presented changes throughout the years, modeling different situations. The growth of areas with eucalyptus crops was linear in all scenarios, however, this growth was stronger in the Pessimistic scenario; and it presented a delayed moderate growth in the Optimistic scenario.

The restrictive areas—conservation units and permanent preservation areas—constituted an important aspect considered in modeling of changes in land use and cover; these areas are important for the conservation and preservation of natural resources, especially in forest remnants.

On average, 97.4% of the total area of the integral protection units were composed of natural vegetation in the Trend scenario over the 40 simulated years, with 2.1% of pasture and 0.01% of forestry areas. Areas with sustainable use had, on average, only 43.6% of natural vegetation, with 46.3% of pasture and 2.3% of forestry areas in this period. The Trend scenario had high averages of pasture and forestry areas for the two types of conservation units in the 40 simulated years compared to the Pessimistic scenario, with 4.4% of forestry areas, and more than half (55.1%) of the pasture areas in conservation units with sustainable use. In the Optimistic scenario, natural vegetation areas increased in 60% in conservation units with sustainable use, which presented the lowest rates of pasture and forestry areas.

The comparison of areas with multiple uses to permanent preservation areas showed the highest rates of pasture (15%) and forestry (1%), and the lowest natural vegetation area (81%) in the Pessimistic scenario. This still is an optimistic scenario, but it shows more pasture area in permanent preservation areas compared to the Trend scenario. However, the permanent preservation areas were composed of 90.2% of natural vegetation and only 0.2% of forestry areas, which is a smaller area than those found in the Pessimistic and Trend scenarios (0.6%).

The modeling pointed out the potential land uses of the Paraíba Valley region, contributing to a more efficient management of this territory, and assisting in directing public policies of incentives, supervision, and planning. The methodology used in this study is developed with geographic data and free software, which makes its application feasible in several political-administrative spheres in other regions, beyond the area under study.

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