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DYNAMIC MODELLING OF LAND-USE INFLUENCE ON BIODIVERSITY IN AN URBAN WETLAND

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ABSTRACT

Urban wetlands play a key role in the ecological structure of cities. Population growth and unsustainable land-use change have led to fragmentation and biodiversity loss in wetlands. The objective of this paper is to show a dynamic modelling study of the influence of land-use change on biodiversity in a wetland of a Latin American megacity (Bogota D.C., Colombia). A multispectral analysis of satellite images was applied to study the change in land use. A dynamic simulation model that considered the relationship between population size, and change in land use, biodiversity, and eutrophication level was also developed. The results suggested as the main indicator variable of the change in land use to population size. During the dynamic simulation, an exponential population growth was observed. Conversely, natural and transition areas of the wetland decreased by 99.6% and 100%, respectively. In this prospective simulation scenario, natural area of the wetland decreased by 5.95 ha/year. Dynamic simulation allowed the development of exponential (R^2 = 0.927), exponential (R^2 = 0.938), and logarithmic (R^2 = 0.998) regression models between the population size, and natural area, biodiversity, and eutrophication level, respectively. This study is relevant for deepening knowledge regarding the use of dynamic models that seek to simulate the conditions of change in land use and biodiversity in urban wetlands.

Keywords: biodiversity, dynamic modeling, eutrophication, land use, population growth, urban wetlands.

INTRODUCTION

Throughout its history, urban wetlands have been subjected to constant pressures that generate a systematic loss of composite, structural, and functional biodiversity. These pressures are associated with both natural phenomena, as well as with the varying degrees of human intervention on these ecosystems [1, 2]. Disruptions from natural causes refer to changes that lead to a natural transformation process in the wetland. For example, disturbances by disconnection with groundwater or events associated with the geomorphological, tectonic, or climate characteristics of the living area where these ecosystems are located [3, 4]. Instead, anthropic disturbances have a direct or indirect origin from human activities such as population growth and the consequent expansion of urban borders, which generate a reduction of natural area in the wetland and its fragmentation. The waste dumping, indiscriminate use of water, direct extraction of fauna and flora, invasion of exotic species, and implementation of extensive productive systems of agriculture, livestock, and grazing can also be considered as anthropic disturbances [5]. All these pressures are likely to generate systematic changes on wetlands, even overcoming their resilience. Namely, adding pressures with its inherent characteristics of vulnerability prevents the wetland from taking on these changes, leading to a loss of ecosystem services, functions, values, and attributes [6].

The wetlands are a natural resource of great relevance, which is recognized worldwide. Between 1970 and 2015, the loss of approximately 35% of the world's natural wetlands is reported [7]. These ecosystems are considered natural landscape filters, which function as water receivers, treat waste from human sources, and can clean up contaminated waters [8]. They also stabilize water supplies, thus mitigating both floods and droughts. Wetlands are used to protect coastlines and recharge underground aquifers, as well as protect their biodiversity [9]. Nevertheless, wetlands are currently highly underrepresented in global environmental models [10].

Additionally, wetlands play a fundamental role in the development of human societies that have inhabited Bogota city (Colombia), are an important part of their ecological structure, and are highly productive and diverse systems [11]. They offer a wide variety of ecosystem services such as flood control, aquifer recharge and discharge, erosion control, sediment and nutrient retention, biomass export, microclimate stabilization, storm-runoff protection, recreation, and tourism [12, 13]. Moreover, these ecosystems play a significant role in being scenarios for the development of spiritual values, myths, legends, and intangible heritage of their surrounding communities [14]. These ecological systems are also part of the landscape of Bogota and are isolated from the Andean high landscape, which favors the evolution for example of endemic birds, especially aquatic birds. The birds are considered as possible indicators of wetland functionality, because the presence of upper links of the trophic chains indicates the functionality of lower groups [15].

The dynamic simulation has been applied to model biological systems, such as the future distribution of species and changes in various ecosystems in the face of varying climate parameters [16, 17]. Indeed, it has also been used to model environmental systems to manage them comprehensively [18]. Thus, dynamic simulation is an important tool, which allows emulating the interactions between the ecological, economic, and social dimensions of a given ecosystem [19]. Currently, wetland modeling has been developed in several fields such as the distribution of species, mainly aquatic plants; and changes in their spatiotemporal dynamics and loss of their natural area [20]. Dynamic simulation has also been used to project future scenarios in relation to water quality variables in the face of pollution and waste dumping problems [21], potential landscape transformations associated with climate change, and the relationship of productive and human development activities in interaction with biodiversity [22]. All previous applications of dynamic modeling have possibly favored an understanding of the ecological functioning of wetlands.

The main objective of this paper is to show a study of dynamic modeling in relation to the influence of land use variation on biodiversity in an urban wetland of a Latin American megacity (Bogota D.C., Colombia). This study will be useful for analyzing the possible relationships between population growth, land use change, eutrophication, and biodiversity. These variables are fundamental to developing environmental conservation and management strategies in urban wetlands.

MATERIALS AND METHODS

Study Site

The wetland under study was in the west of Bogota city, Colombia (4°43’17’’N; 74°08’20’’W). The natural area of the Jaboque wetland for 2012 was 152 ha (Figure 1). This is an ecosystem of importance to the ecological structure of the city. Nevertheless, it shows problems such as deforestation, grazing, habitat loss from grass rooting, and debris deposit. These changes in land coverage have led to the significant loss of biodiversity, which is made up of a large group of invertebrates and vertebrates. These species provide ecosystem services of support, regulation, and supply in the trophic chain of the wetland. Around the wetland under study most of the land is intended for residential use, and potatoes, strawberries, and vegetables crops. The wetland is a hydrological unit belonging to the Bogota River basin, located on a river and lake plain, fed by rainwater, and in winter season, it functions as a flood buffer of that river [23].

Spatiotemporal Analysis

Multispectral treatment was used to extract thematic information from satellite images in a simple and semi-automatic way. During the classification, each pixel of the satellite image was assigned a class through a selection of training signatures, and the software used these signatures as decision ranges to assign each pixel to one class or another in land use [22]. In this study, satellite images were taken from the United States Geological Survey (USGS) (https://www.usgs.gov/science-explorer-results?es=Bogota). These satellite images included monthly and annual temporality changes in land use, and variations in atmospheric variables (cloudiness). This allowed identifying variations in land use with respect to natural (wetland), transition (grasslands, crops, and green areas), and urban areas around the wetland under study. This analysis of the variation in land use was carried out between 1987-2014. Thus, dynamic relationship between population characteristics and land use around the wetland was studied. This also allowed analyzing changes in their biodiversity, fragmentation, habitat loss, and trophic status.

Additionally, filters to improve satellite images and make their interpretation more efficient were applied. An analysis of satellite images by digital and visual monitoring was also performed. In both cases, spectral signatures were defined, and a range of pixels corresponding to a given land coverage was selected [22]. Thus, the satellite images were integrated into a geographic information system and a zoning of the area studied was obtained. The Envi 5.0 and ArcGis 10.2 software were used for satellite image analysis, and their main features were as follows: i) Envi 5.0 was a software for visualization, analysis, and presentation of digital images that was easily integrated with ArcGis. This was mainly used for spectral analysis, geometric correction, terrain analysis, and cartographic information management. ii) ArcGIS 10.2 software enabled the collection, administration, organization, sharing, and distribution of digital geographic information [24].

Dynamic Modeling

In relation to the structure of the dynamic model, it consisted of two sub-models (Figure-2). The first sub-model was developed to explain the change in land use in the wetland under study [25]. The second sub-model was developed to explain the possible changes in biodiversity because of the relationship between population size and increase of total phosphorus in the wetland (eutrophication) [26]. Initial information on total phosphorus as well as information on bird and plant richness was obtained from the environmental management plan of the wetland under study, which was provided by the Aqueduct and Sewerage Company of Bogota [23].

Figure-1. Location of the urban wetland under study (Google Earth Pro, 2021).

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The simulations were carried out using the Stella V.10.1. software. The variables of the conceptual model were transformed into algorithms [20]. This is to establish the associations between the model variables and perform the established simulations. The variables used in the model were as follows: (i) Natural area (wetland), corresponding to the entire ecological system, including the water mirror and vegetation (ha). (ii) Transition area, corresponding to the area of grasslands, crops, or non-urban land uses (ha). iii) Urban area, represented in buildings that marked a change in the matrix where the natural and transitional area was found (ha). iv) Area available, corresponding to the total area in the study wetland, 148 ha. v) Population size in the area of influence of the wetland (inhabitants). vi) Population density (population/ha). vii) Population growth rate, which was calculated considering the number of people added to the population each year considering birth and mortality rates (Figure-2). The normality of the data series for the variables under study was evaluated using the Shapiro-Wilk test (p-values > 0.05).

Additionally, dynamic model considered the eutrophication index (TSIPt). The calculation of the eutrophication index was made from the Carlson's equation [27]. This equation was based on the total phosphorus content (Pt) of the ecosystem (TSIPt = 14.42*Ln[Pt]+4.15). Changes in biodiversity were also included in the dynamic model, and these were determined from the guidelines established by Eppink *et al.* [5]: (i) Plant richness = 20/(eutrophication level/10)+0.0913. ii) Bird richness = (100*natural area)+(0.01*agricultural area). Lastly, the Monte Carlo method was used to estimate the model sensitivity. Sensitivity tests were applied to independent variables linked to dynamic sub-models of changes in land use and biodiversity. A Pearson correlation analysis between variables was also applied to determine the reciprocity percentages or ability of one variable to explain or modify the behavior of another. The determination coefficient was also calculated to measure the goodness of fit of the dynamic model developed [28]. Lastly, regression models between the variables considered were also developed.

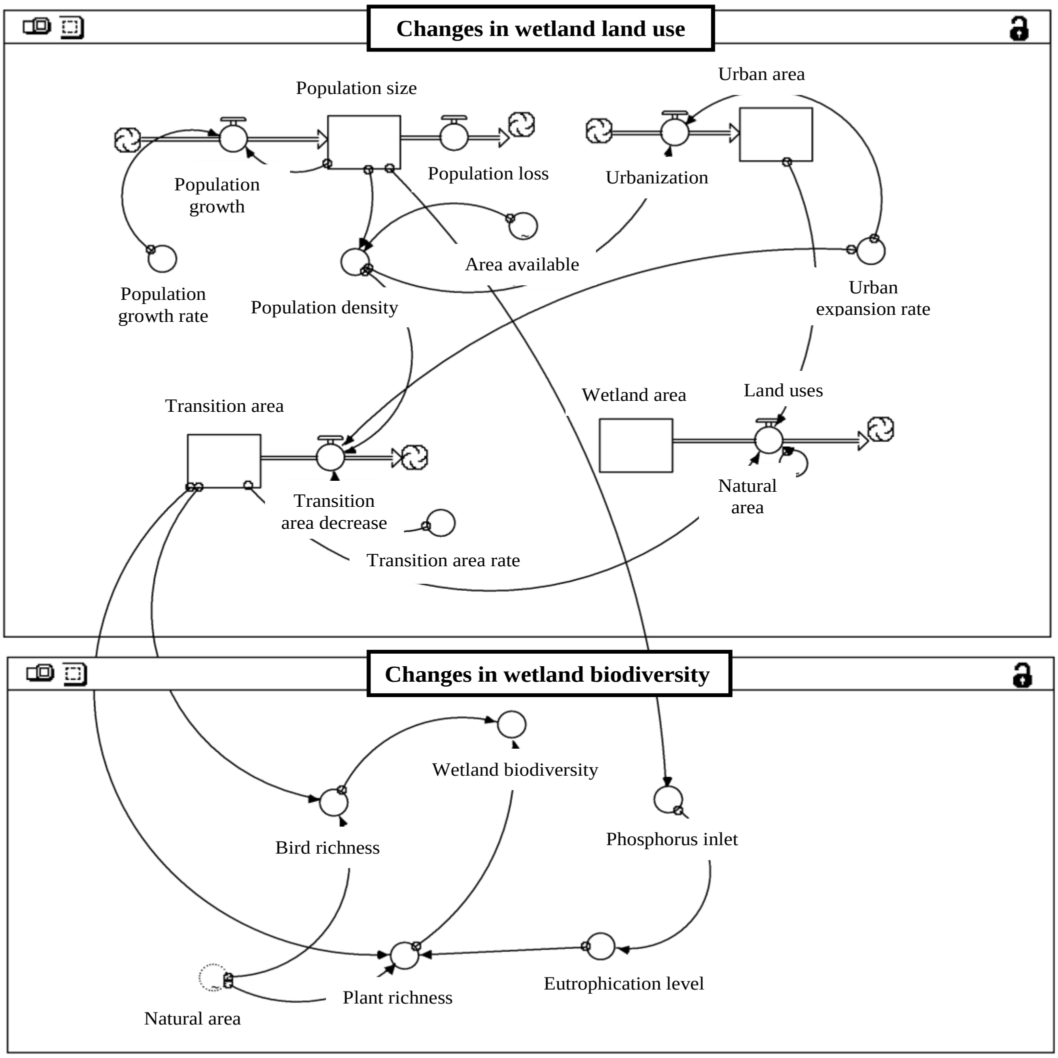

Figure-2. The conceptual model for dynamic simulation.

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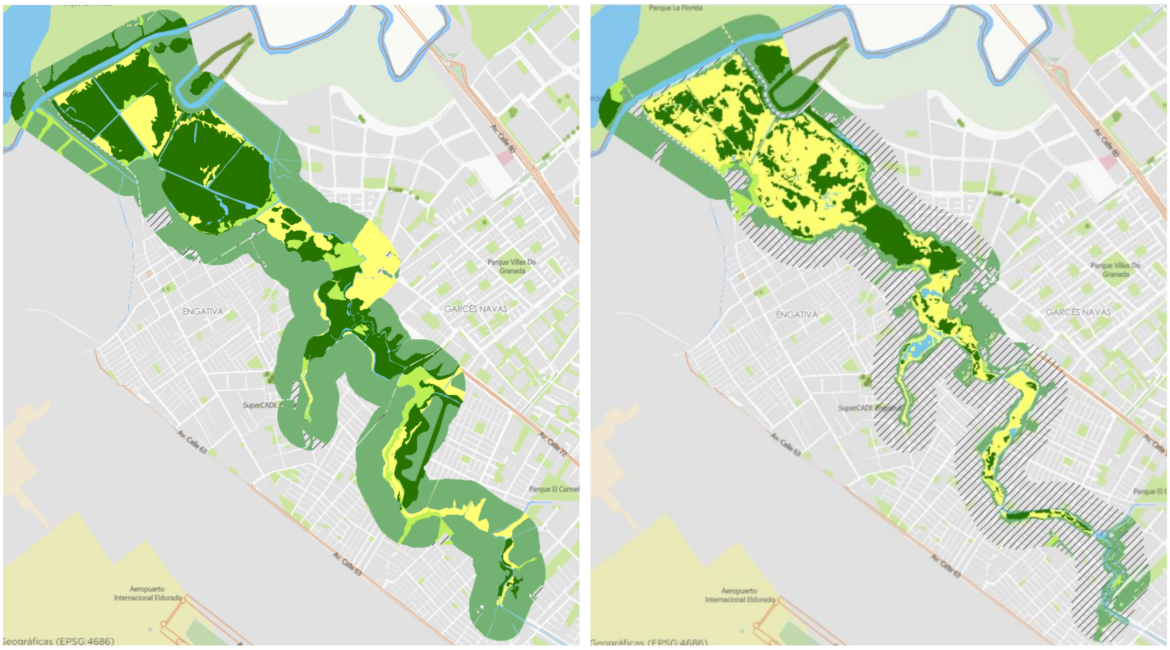
RESULTS AND DISCUSSIONS

The results of the retrospective interpretation of satellite images showed changes in land use during the period 1987 - 2014. Namely, an increase in land for urbanization was observed, which began with small patches that were consolidated into a single urban matrix with few transitional land corridors. Indeed, spatiotemporal analysis initially suggested that urbanization, because of population growth, was possibly the main cause of natural area loss in the wetland. Figure-3 shows the variation in land use during the retrospective study period. The findings showed that during this period 329.6 ha were urbanized, of which 52.7 ha corresponded to natural area (15.9%) and 276.9 ha corresponded to transition area (84.1%). For example, Smith and Romero [29] also detected through satellite images that urbanization replaced natural and semi-natural areas in Concepción City (Chile). This affected 40% of the city's total wetland area. The results obtained from multispectral analysis were used to feed the dynamic model developed for prospective analysis.

The results of the dynamic simulation under a prospective scenario of 25 years (t) showed that the population size (PS) in the area of influence of the wetland would increase, from 111397 inhabitants to 263258 inhabitants (+136%). Population density would also increase by 1825%, from 47.8 inhabitants/ha to 920 inhabitants/ha (Figure-4). Thus, the results of the dynamic simulation showed an exponential increase in population size ($PS = 111397 * e^{0.0344*t}$; $R^2 = 0.998$). Conversely, the natural area of the wetland would decrease from 1687 ha to 6.99 ha (-99.6%). The transition area would also decrease, from 712 ha to its total loss (-100%). Population growth and consequent urbanization did not bring with them only human populations, they also brought the consequences of economic development activities that were established in everyday life and that generated by their lack of knowledge conflicting patterns of relationship with ecosystems [30]. This probably increased the vulnerability of the species and decreased the opportunity to enjoy the ecosystem services that the wetland provided to the city.

Additionally, the transition area was inversely proportional to population size (r-Pearson = -0.989; p-value < 0.001), population density (r-Pearson = -0.886; p-value < 0.001), and urban area (r-Pearson = -0.964; p-value < 0.001). In this study, and under an urban context, the results suggested that increasing population density decreased the transition area of the wetland (Figure-4). Nevertheless, and in a rural context, Eppink *et al*. [5] reported an opposite trend in developing a land-use decision model. These researchers reported that increasing population density also increased the land used for agriculture (transition area), resulting in a reduction in natural area and biodiversity loss. In other words, and depending on the urban or rural environment of the wetland, buildings or crops could replace the transition areas. Lastly, the findings also hinted that local authorities should more effectively control the current occupation processes of the area of influence of the wetland under study because a strong trend in reducing their natural area was observed during dynamic simulation (-5.95 ha/year).



a) b)

Figure-3. Spatiotemporal variation in land use of the wetland under study. a) 1987 and b) 2014 (https://mapas.bogota.gov.co/).

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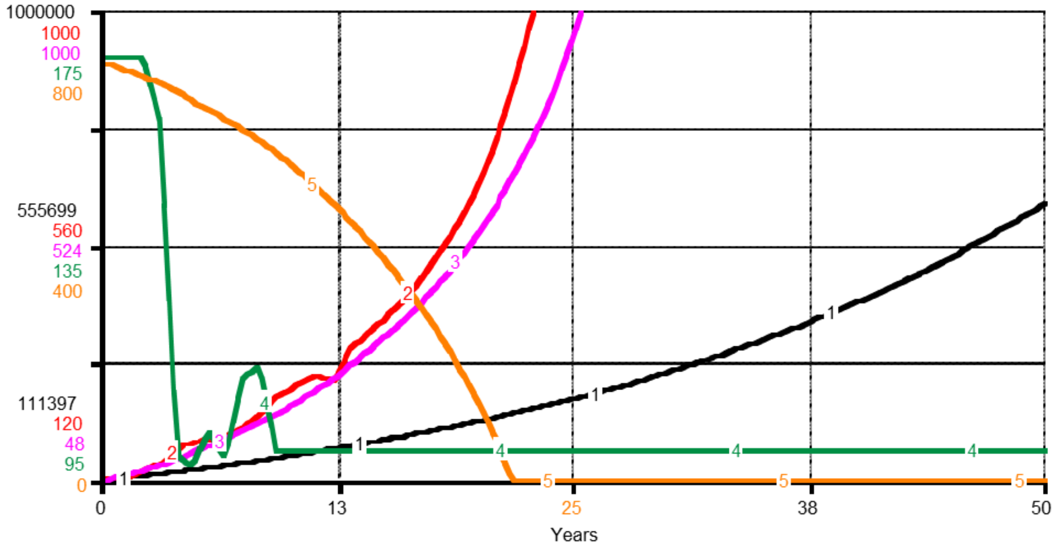

Figure-4. Population and land-use dynamics in the wetland under study. 1 = Population size, 2 = Population density, 3 = Urban area, 4 = Natural area, and 5 = Transition area.

An analysis with Pearson's coefficient showed significant correlations between all simulated population and land use variables. On average, the results showed that the variables with the best correlations were the urban area followed by population density (Table-1). Thus, the results initially suggested these two variables as possible indicators of the change in land use of the wetland under study. Indeed, the urban area showed direct and very strong relationships with population size (r-Pearson = 0.978; p-value < 0.001) and population density (r-Pearson = 0.976; p-value < 0.001). Hence, population size could also be considered as an indicator variable of land use change in this study. The results suggested that the indicator variable that was best associated with the loss of natural area (NA) of the wetland was the population size (PS) (r-Pearson = -0.574; p-value < 0.001). A regression model between these two variables was developed, and the exponential trend was that of best fit (NA = $267184 {*} e^{-0.005 {*} PS}$; R^2 = 0.927). Lastly, the urban area also showed a very strong and inverse relationship with the transition area (r-Pearson = -0.964; p-value < 0.001).

In relation to the prospective dynamic simulation of biodiversity changes (BIO), the results showed that biodiversity would decrease by 99.1% in 25 years. Specifically, the richness of birds and plants would decrease during the simulation period by 97.0% and 100%, respectively (Figure-5a). The findings showed an exponential decrease in wetland biodiversity during the prospective period (BIO = $327.7 {*} e^{-0.155 {*} t}$; R^2 = 0.885). Thus, the results suggested that progressive loss of natural area and fragmentation of the ecosystem possibly had negative impacts on biodiversity. Namely, this possibly changed the distribution and abundance of species due to migration and immigration processes, which altered intra- and inter-specific relationships in the ecosystem [31]. This fragmentary phenomenon probably generated physical barriers that limited and prevented the reproduction of species, minimizing genetic recombination, promoting inbreeding, and genetic drift. Hence, there was possibly a decrease in the evolutionary and adaptive options of individuals and their species [32].

As mentioned, natural area of the wetland decreased by 99.6% during prospective dynamic simulation (25 years). Indeed, the natural area showed a direct relationship with wetland biodiversity (r-Pearson = 0.985; p-value < 0.001) (Table-2). Similarly, the same trend was evident with the bird richness of birds (r-Pearson = 0.982; p-value < 0.001) and plants (r-Pearson = 0.997; p-value < 0.001). On this matter, Mao *et al*. [33] reported that changes in bird biodiversity were possibly due to land-use change processes, which also influenced floristic composition of the ecosystem. This indicated that the birds were closely linked to the structure of plant communities. Birds also evolved and related to their habitat by availability of food, space, nesting resources, predator protection, and specific resources for courtship and reproduction [34]. The findings suggested that the indicator variable that was best associated with wetland biodiversity was population size (r-Pearson = -0.910; p-value < 0.001). Thus, a regression model was developed between these two variables and the exponential trend was the one that showed the best fit (BIO = $5020.6 {*} e^{-0.00003 {*} PS}$; R^2 = 0.938).

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Table-1. Pearson´s correlation coefficients between simulated population and land use variables.

	Population size	**Urban area**	**Natural area**	**Population density**	Transition area
Population size	**1.00**				
Urban area	0.978	1.00			
Natural area	-0.574	-0.466	1.00		
Population density	0.916	0.976	-0.389	1.00	
Transition area	-0.989	-0.964	0.528	-0.885	1.00

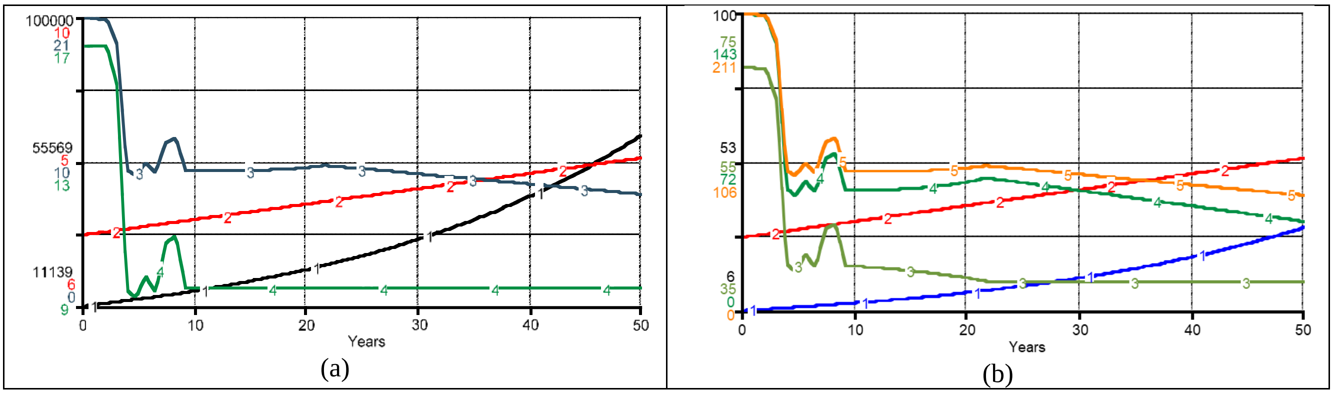

Figure-5. Biodiversity in relation to population size and eutrophication level of the wetland under study. a) Biodiversity and population size: 1 = Population size, 2 = Eutrophication level, 3 = Biodiversity, and 4 = Natural area; b) Biodiversity and eutrophication level: 1 = Population size, 2 = Eutrophication level, 3 = Bird richness, 4 = Plant richness, and 5 = Biodiversity.

Table-2. Pearson's correlation coefficients between variables of population, land use, biodiversity, and eutrophication level.

	Population size	**Eutrophication level**	**Bird richness**	**Plant richness**	**Biodiversity**	**Natural area**
Population size	1.00					
Eutrophication level	0.993	1.00				
Bird richness	-0.959	-0.966	1.00			
Plant richness	-0.882	-0.917	0.966	1.00		
Biodiversity	-0.910	-0.938	0.982	0.997	1.00	
Natural area	-0.954	-0.963	0.999	0.969	0.985	1.00

The results of the dynamic simulation suggested that while the population size increased, the inflow of phosphorus to the wetland also increased. Thus, an increase in eutrophication index during the prospective simulation period was observed (Figure-5b). The wetland would change from a mesotrophic status to a eutrophic status in 50 years. The correlation between population size (PS) and eutrophication level (EU) was direct and very strong (r-Pearson = 0.993; p-value < 0.001) (Table-2). A regression model was developed between these two variables, and the logarithmic trend was the one that showed the best fit (EU = 14.422*Ln(PS)-138.68; R^2 = 0.998). In this study, the eutrophication level increased by 42.9% during the simulation period. A regression model was also developed, and the linear trend was the one that showed the best fit (EU = 0.4961*t+28.914; R^2 = 0.986). Although eutrophication is a natural process, high phosphorus levels complex the process because the primary productivity of plants, algae, and bacteria is increased. This favors the predominance of some macrophytes species that induce wetland-drying processes and aggravate their fragmentation [35].

As stated, natural area of the wetland decreased by 99.6% during prospective dynamic simulation. Indeed, the natural area of wetland showed an inverse and very strong relationship with its eutrophication level (r-Pearson = -0.963; p-value < 0.001). On this matter, Ehrenfeld [36] reported that urbanization was associated with significant phosphorus contributions into natural ecosystems, mainly by the discharge of untreated domestic and industrial wastewater. This researcher also reported that urbanization generated conditions that favored increased phosphorus

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concentrations. For example, by the construction of drainage systems and impervious surfaces that affected the hydraulic retention time of wetlands. This generated high phosphorus levels, which changed the physical and chemical characteristics of the water and caused biological changes in the ecosystem [37].

Additionally, the biodiversity loss and increased eutrophication of the wetland were possibly associated with point and diffuse discharges of pollutants from urban and transition areas. They could also be related to the loss of natural area and the land urbanization for other uses such as grazing and agriculture. Beltrán and Rangel [38] reported similar results in urban wetlands. In fact, economic development activities such as agriculture, livestock, and grazing affected wetland biodiversity. Nevertheless, these lands were probably constituted in buffer zones of the natural area, and these were less aggressive than the urban matrix developed around the wetland under study. Namely, in terms of landscape function, it was better that the wetland was surrounded by areas of crops and pastures than that it was isolated in urban matrices. In this regard, Hoffmann [39] studied alternative and sustainable ways to develop livestock activities without putting biodiversity at risk with aggressive production systems. These researchers reported the possibility of using lands for economic development activities as protective areas of natural nuclei that housed more biodiversity (e.g., wetlands).

Finally, the dynamic model developed was validated from a sensitivity analysis. The correlations and determination coefficients (R^2) of the linear models observed among the study variables were also considered. Figure 6 shows the results of the sensitivity analysis performed, which validates, for example, that the variable population size explained the behavior of biodiversity loss and the eutrophication level of the wetland under study. The results showed that the variable population size explained by 82.8% and 98.6% the behavior of the variables biodiversity and eutrophication level, respectively. Moreover, this variable also explained in 95.6%, 32.9%, and 97.8% the behavior of the variables urban area, natural area, and transition area. The findings suggested that the low percentage of explanation of the variable natural area was possibly due to the fact that urbanization processes first generated a deterioration of the transition areas, and once they were devastated, the phenomenon of urban expansion affected the natural area of the study wetland.

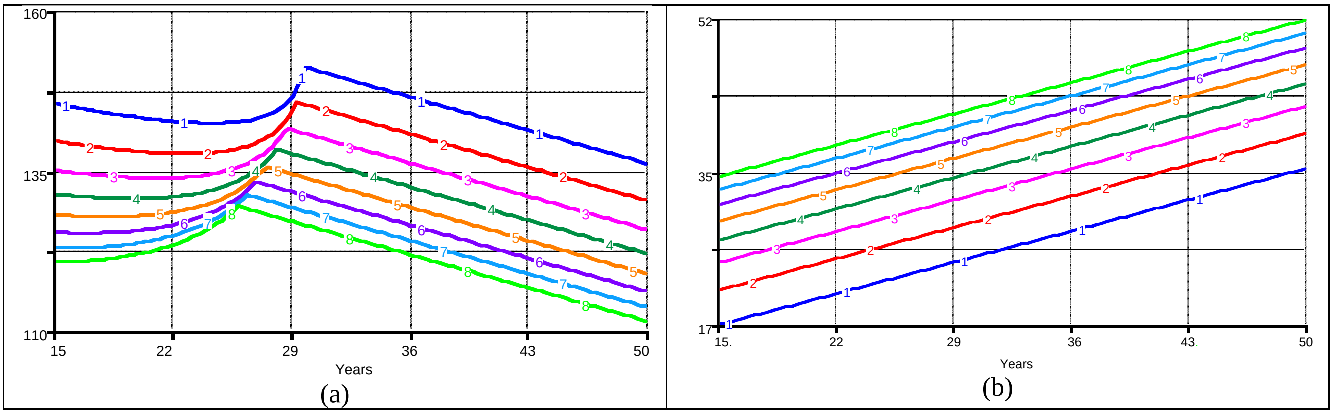

Figure-6. Sensitivity analysis for the developed dynamic model: a) Population size versus biodiversity, and b) population size versus eutrophication level.

CONCLUSIONS

This study allows visualizing the following conclusions from the dynamic simulation developed on this urban wetland.

- The results suggest as possible indicator variables to study the change in land use and biodiversity of the wetland to population size and urban area. These variables show the best correlations compared to the other variables considered in this study (r-Pearson between 0.466 - 0.993).
- The findings show exponential population growth in the area of influence of the wetland located in this megacity. Over a prospective 25-year horizon, the population size will increase by 136%. Conversely, the natural and transitional areas of the wetland will decrease by 99.6% and 100%, respectively. In this prospective simulation scenario, natural area of the wetland will decrease by 5.95 ha/year.
- The results suggest that, under an urban context, wetland transition areas will be replaced by urbanized areas. In contrast, under a rural context, wetland transition areas may be replaced by areas for crops or agricultural activities. In this study, there is a very strong inverse correlation between the transition area and population size in the area of influence of the wetland under study (r-Pearson = -0.989).
- Considering population size as the main indicator variable, exponential (R^2 = 0,927), exponential (R^2 = 0,938), and logarithmic (R^2 = 0,998) regression models are developed to simulate the behavior of the natural area, biodiversity, and eutrophication level of the urban wetland under study, respectively.
- Finally, this study is relevant to deepening knowledge regarding the use of dynamic models that seek to simulate the change conditions in land use and biodiversity in urban wetlands. Indeed, this study will

also be useful for agencies and institutions responsible for the control and monitoring of this type of ecosystem in urban areas.

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CONFLICTS OF INTEREST

The author states that there is no conflict of interest.

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