Modelling Transport-based Land-use Scenarios in Bogota

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Abstract: Economic growth experienced in Colombia since 2001 has impacted on heavier traffic levels in the capital city of Bogota which in turn have worsened air pollution indicators and environmental public health conditions. Different political options competing at municipal elections have included their respective proposals for public transport in their programs. Impact expected from each of these scenarios makes it necessary to implement models allowing their assessment. Given this need, we present the Bogota Land Development Model (BoLD), a practical implementation of a Land-use Cover Change (LUCC) simulation based on two different public transport scenarios; a highway-based network and a suburban rail system. Transport scenarios are combined with options to expand the city into natural reserves. Customized geospatial analyses were developed for calculating accessibility distance decay factors based on overtime-spatial decay determination (OSDD) method. Results of the scenarios are presented both in maps and in "mobility circles". Validation of the results suggests that OSDD and the mobility circles appear to contribute to better information to decision-making when evaluating urban scenarios driven by transport projects.

1 INTRODUCTION

Increasing traffic congestion and public and political debate about the need of more sustainable transportation modes are current hot topics in Bogota. In response to this debate, a Land-use Cover Change (LUCC) model to evaluate transport alternatives for the Bogota western growth areas is presented. The model, called the Bogota Land Development model or BoLD, uses Metronamica software. BoLD was conceived to address the need to understand global impacts on the urban development of transport infrastructure projects. This is particularly important for a city that has had its political agenda driven by transport projects.

2 METHODOLOGY

2.1 Study Area

Although other areas of the city have had significant debate in terms of its growth (for example, the South for low income population and the North for the rich), stakeholder workshops as well as current administration priorities brought our attention to the West growth area (Universidad de Los Andes 2015). Thus, the study area was determined by the city of Bogota and the main surrounding municipalities located to its West. These are: Funza, Mosquera, Madrid, Focatativá, Cota and Soacha (figure 1). All together add a total of 7.5 million inhabitants of which Bogota holds 6.5 million (DANE 2011).

2.2 Infrastructure and Land Development Proposals for Bogota

For the West, transport proposals have aimed to either increase current road infrastructure for buses or to create a new suburban rail service running on the existing freight infrastructure (Regiotram 2014).

The Light Rail Transit (LRT) is planned to be developed as a public-private partnership between private investors, the city of Bogota and the State of Cundinamarca. The LRT objective is to supply a fast, environmentally-aware, safe and integrated transport option for the West. It is intended to provide users with an alternative to the current road-based public transport (Regiotram 2014). The proposal is that it will operate as a commuter train in the inter-urban areas outside Bogota, and as a

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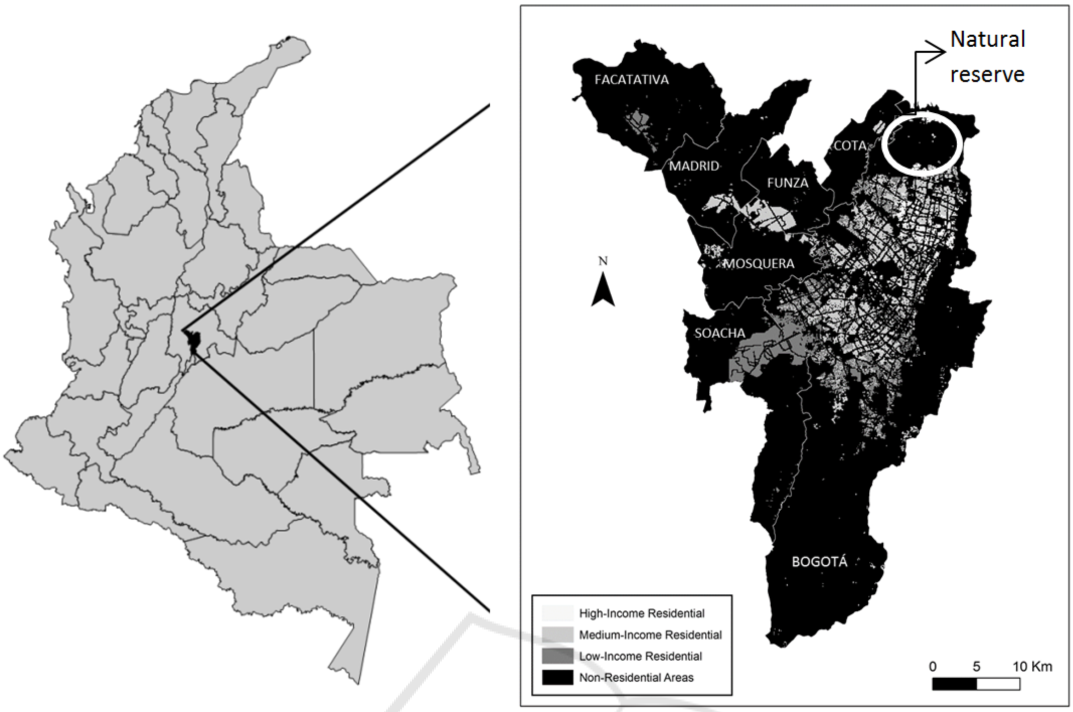


Figure 1: Study area, income-based residential areas modelled and location of natural reserve.

tramway in Bogota's urban areas, reaching speeds of 110km/h and 60 km/h respectively (Regiotram 2014).

Instead of the LRT, the road proposal includes road improvement in the Western and Northern parts of the city. It involves constructing urban highways to replace some of the roads that connect Bogota CBD to other town centres.

To complement these infrastructure scenarios, the Van Der Hammen reserve (VDH), a 1400 hectares of natural reserve in Bogota's North, has been included in the analysis. Supporters of developing the reserve argue that having available land for residential developments close to existing commercial and industrial areas would provide shorter travel distances. These benefits, combined with sensible urban development, could potentially surpass benefits of maintaining the land as an environmental reserve (El Tiempo 2016).

Considering these options, four scenarios were set to be modelled in BoLD (table 1).

2.3 Data Collection

In order for the implemented model to be able to deal with the four proposed scenarios, a large range of data sets were required.

Table 1: Scenario narratives in BoLD.

	Road infrastructure	Suburban train infrastructure
Natural reserve maintained	Scenario 1: Road infrastructure continues to be the main source of transport for growth areas in the West. New roads allow additional connections between municipalities and Bogota. No changes to existing restrictions to urbanization in the VDH reserve.	Scenario 2: Existing freight rail infrastructure upgraded to provide a suburban service for passengers in Bogota and municipalities in the West. New road constructions or upgrades are limited to areas were no infrastructure currently exists.
Natural reserve urbanized	Scenario 3: As in scenario 1, roads are upgraded to provide accessibility in the West. However, land regulations are changed so VDH reserve is urbanized by providing additional road infrastructure as well as BTR services.	Scenario 4: As in scenario 2, a new train service is developed for the West. However, land regulations are changed so the VDH reserve is urbanized by providing additional road infrastructure as well as BTR services.

A LUCC model is typically calibrated by providing two different datasets of the study area (Straatman 2004). Generally, these datasets need to be separated in time by around 10 years to meet the LUCC dynamics (Hewitt et al. 2014). The calibration process consists on replicating the LU map of the second date with a sufficient level of similarity to the actual LU map. The goodness of the model can be assessed by means of both qualitative and quantitative methods (Hewitt et al 2014). The model is then extended to the final simulation date.

In the BoLD case, the calibration process was substituted by the application of the neighbouring rules and accessibility analysis. Although this may be arguable, literature shows that calibration assessment is still a challenge and indices such as kappa and others are highly criticized (Pontius and Millones, 2011). Thus, visual assessment of calibration (van Vliet et al 2012) can be considered as good. Besides, the perceived value of these models is shifting from their very arguable predicting capacity to their usefulness as a tool for share-learning throughout the modelling process (Escobar et al 2015).

Multiple datasets were explored. Cadastral or planning datasets containing complete land-use cover in two different years was only obtainable for the Bogota municipality. Municipalities in the West did not have complete information and, therefore, a combination of datasets (mainly Landast imagery) was used to produce a complete dataset of land-use cover for both the baseline and the calibration years. Although the time lapse is only 9 years (2005-2014), the rapid growth experienced in Bogota during those years has resulted in more than sufficient amount of LUCC as to properly calibrate the model. In order to address limitations to Landsat images additional data sets were sourced. Table 2 describes them and shows how they were used to improve information from the Landsat images.

Table 2: Datasets adopted for the BoLD Model.

Dataset	Description	Application in BoLD
2014 cadastral dataset for Bogota	Parcel-based cadaster dataset for Bogota that includes land-use coverage for every land parcel and the fiscal land value of them	Calibration of land-use coverage areas in Bogota
2005 to 2011 planning zones	Planning zones for areas outside Bogota municipality with their intended or authorized land-use coverage	Calibration of land-use coverage areas in Bogota by detecting vacant zones and more likely land-use based on regulatory restrictions
2005 and 2014 water body inventory	Official dataset of rivers, lakes and other water bodies in the area	Determination of areas covered by water not always identifiable by Landsat images
2005 and 2014 national and regional parts and reserves	Official dataset from national government describing legally environmentally protected land in the study area	Separation of parkland from agricultural lands as well as identification of forest reserves

2.4 Model Implementation

In a general sense, a LUCC model based on cellular automata requires inputs (of both information and parameters) in the following areas:

a. Future land demands
b. Current and future land zoning changes and suitability conditions
c. Neighbouring relationships between land-uses, and
d. Accessibility analysis based on transport infrastructure.

a. Future land demand inputs were developed based on forecasting current growth trends. Demands for the three income levels of residential land-uses modeled (figure 1) were based on population growth forecasted by the National Statistics Department (DANE 2016). The other two key land-uses included in the model, commercial and industrial, were projected based on the GDP expected by the Bogota and its surrounding region (DANE 2016; DANE 2016b). According to reports from the Bank of the Republic, the industry is projected to grow 2.7% for the next 2 years. FENALCO (National Federation of Retailers) has estimated that for the next two to three years the commercial activity is likely to grow around 3% (FENALCO 2014).

DANE and FENALCO data were used to estimate future land demands in residential and in commercial and industrial respectively. In order to

Table 3: Population growth projection. (Based on data from DANE and FENALCO).

Year	2005	2014	2023	2032	2040
Total Population (People)	7.556.515	8.661.781	9.737.843	10.808.780	11.760.724
Total Commercial (mill COP - GNP)	69.324	152.931	201.478	262.883	333.012
Total Industrial (mill COP - GNP)	29.119	51.215	61.807	73.865	86.544

estimate future land demands for a city, information provided by a national entity (Mancosu et al. 2015; Aljoufie 2014) or land demand estimated by researchers (Hewitt et al. 2012) can be adopted. This is the rational for obtaining the projections for population growth by mathematical extrapolation. The extrapolation was divided into 4 different periods of the same number of years each, thus land demand was known for 2005-2014 and estimated for 2023, 2032 and 2040 (table 3).

Based on the expected growth, the number of hectares for the increase in land demand for future years can be observed in the table 4.

b. Model inputs were sourced from local zoning regulation data. Following experiences of other developing cities (Lombard 2014; Heinrichs and Bernet 2014), growth of residential areas is not strictly limited to authorized or permitted areas. Informal settlements are still common. In Bogota construction outside authorized areas is still a significant problem for low-income residential land-use (Escobedo et al. 2015).

Bogota and its neighbouring municipalities do not have an integrated land planning system. This leads to land-use plans that are often inconsistent. After reviewing all land-use planning zones in all municipalities, the following zoning categories were included into BoLD:

- Archaeological: All areas having archaeological elements of value.
- Heritage: All areas that have historical and cultural character, which must be preserved and protected as they are part of fabric of each culture or nation.
- Environmental Restriction: All areas that have a strategic role in biological processes and contribute to biological diversity; as well as the provision of basic resources for human subsistence.
- Industrial Use: All areas that currently have high industrial activity. Road network: All areas through which traffic flows.
- Environmental slightly restricted: All areas that have a strategic role in biological processes and contribute to biological diversity; however, they are not protected or are already fragmented or affected by human activity.
- Airport: Whole airport area.

A similar procedure to zoning was performed for including suitability in BoLD. Suitability refers to natural conditions under which land-uses develop. The regional risk management authority provided the information used. In BoLD, the suitability was evaluated by landslide, flood zones, heavy rounds and ponding.

c. Neighbouring interactions are fundamental in a LUCC model. To represent them, a methodology based on spatial analysis and Laplace probability

Table 4: Estimated land demand.

Year	**2014**	**2023**	**2032**	**2040**	**% Cells per land-use for** 2040
Residential High Income	1359	1411	1566	1704	4,22
Residential Medium Income	11607	15519	18530	21582	53,41
Residential Low Income	7949	6584	6003	5112	12,65
Commercial	1146	1510	1970	2495	6,18
Industrial	5633	6798	8124	9519	23,55
Total **Cells**	27694	31821	36193	40412	**100,00**
Cells Increment (%)		13%	12%	10%	

concepts was used (Hansen 1993). This methodology was taken from Laplace´s rule formula and adapted for the BoLD model using ArcGIS to calculate distances between land-uses and their relation to land-use cells in a defined searching radius.

$$X_{AB} = \frac{\sum_{i=1}^{n} \overline{D_{AB}}}{R * n} \qquad (1)$$

Where,
A= Land-use A
B= Land-use B
D_{AB} = Distance between A and B
R= Searching radius
n= Number of cells in A
X_{AB}= Attractiveness Index of A to B

d. Accessibility is the level of transport service provided in a specific area. For LUCC models, accessibility refers to the preference of most land-uses to locate closer to transport services. A highly accessible location is more likely to be developed. Mathematically, accessibility in a LUCC model based on cellular automata can be expressed as (RIKS 2007):

$$A_{c,y,s} = \frac{a_{y,s}}{{}^{t}d_{c,y} + a_{y,s}} \qquad (2)$$

Where:

- $A_{c,y,s}$ is the accessibility of cell, *c*, in relation to a certain type of node or transport link, y, (for example, a main road or train station) for a specific land-use, *s*
- $a_{y,s}$ is the accessibility distance decay factor (ADDF) which varies depending on the type of infrastructure, *y*, and it is individual for each land-use, *s*
- ${}^{t}d_{c,y}$ is the distance to the specific cell being analyzed to the infrastructure, *y*, and at a specific time, *t*

Result from this equation can only have a value between 0 and 1 for each cell. As the scenarios being modeled determine distance to the nearest transport infrastructure, assigning ADDF for each type of infrastructure considered and for each land-use is a key task for the modeler.

Although the determination of ADDF is commonly based on empirical experiences (Furtado 2009), the significance of these factors required us to explore advanced technical approaches to determine ADDF. A methodology based on GIS was used to determine ADDF. We have called this methodology OSDD (Overtime Spatial Decay Determination).

OSDD is based on three principles. The first is that ADDF factors are usable for modeling future scenarios.

The second assumption is that ADDF for each type of infrastructure and for each land-use is proportional to each other. In other words, if two ADDF for two different infrastructures are equal they have the same contribution to the overall attractiveness of cells in the model. Consequently, and considering that OSDD creates ADDF with values between 0 and 1, specific transport infrastructure, *y*, for particular land-uses, *s*, has a low proportional accessibility, OSDD would assign a value of 0.

The third principle considers that the average distance between cells within 2 km of a particular land-use and the infrastructure is a good indicator of the ADDF. In consequence, the larger the average distance, the smaller the decay factor would be.

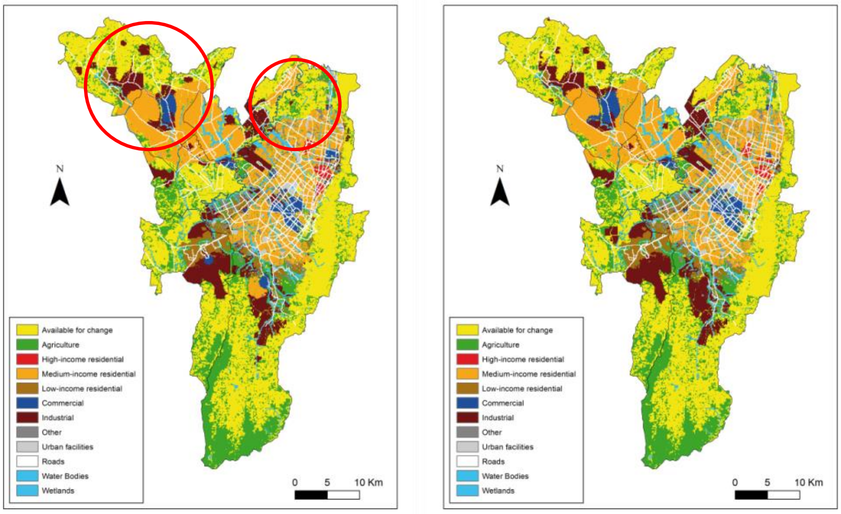
The results of applying OSDD are ADDF values between 0 and 1. Additionally, and considering that transport infrastructure could be modeled as lines or points in a GIS system, double normalization is conducted.

Using processed datasets for 2005 and 2014 in the BoLD model, OSDD was applied and the results were compared.

3 RESULTS

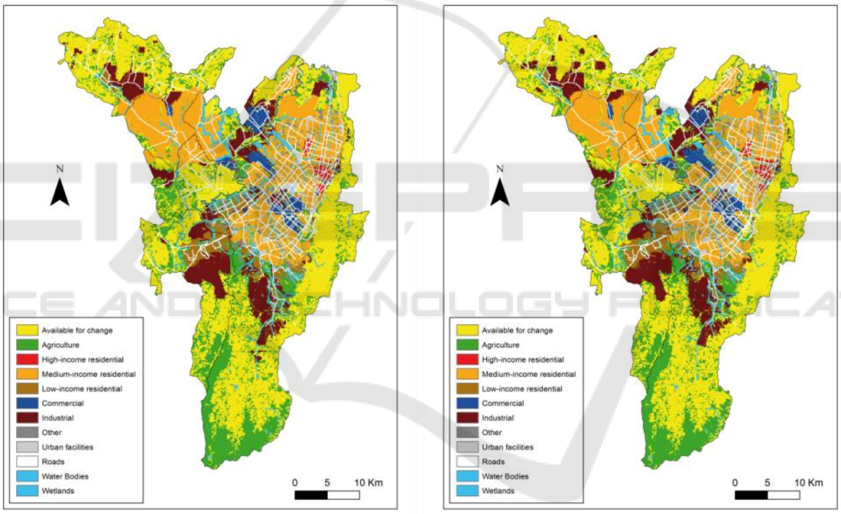
After implementing BoLD using the parameters described in the previous section, including de ODDC for accessibility analysis, results were obtained for all scenarios. Maps results of the baseline year (2014) and the simulated result for 2040 for each scenario are presented in figure 2.

General patterns of development are maintained in all scenarios. This is probably due to the fact that Bogota is a mature city in where trends have been in place for many years. However, there are differences in specific zones between scenarios (highlighted with red circles). For the first scenario, increased commercial development along the proposed road with additional industrial in their surrounding areas can be noticed. Also, industrial areas in the far West appear among farming zones. These two are expected results as additional road capacity is particularly attractive to commercial and residential.



Scenario 1: Highway development and VDHR restricted

Scenario 2: Train and VDHR restricted



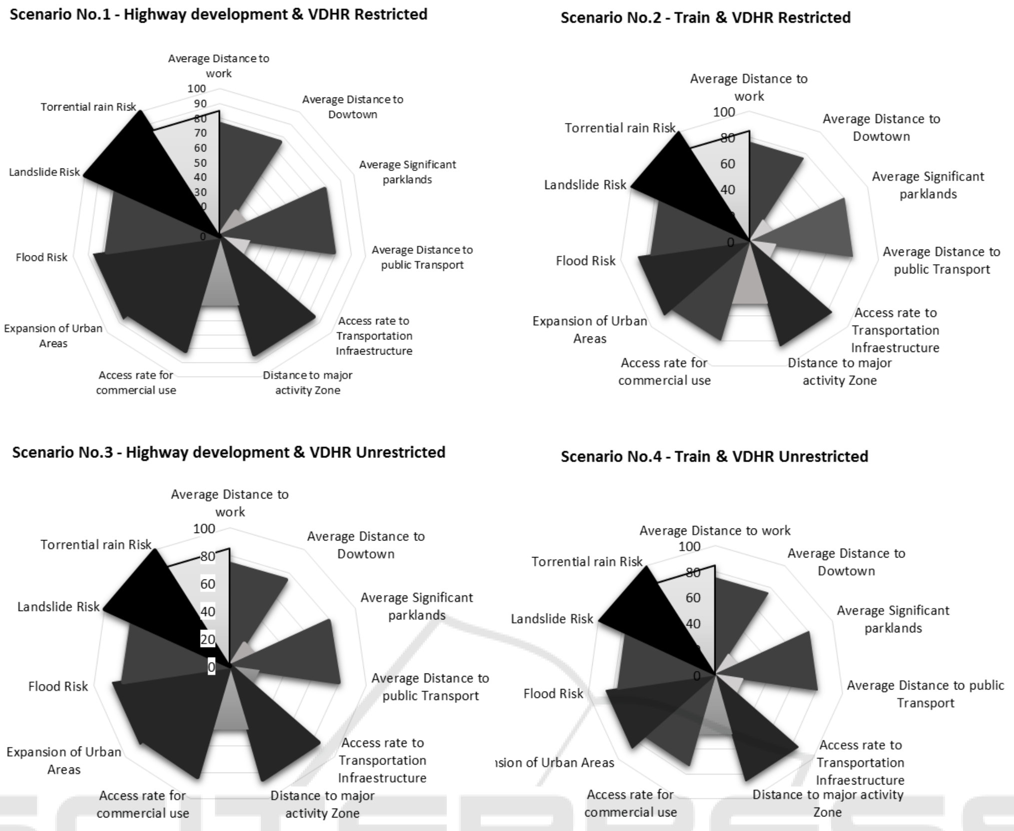
Scenario 3: Highway development and VDHR unrestricted

Scenario 3: Train and VDHR unrestricted

Figure 2: Resulted land-use maps for 2040 scenarios.

For the rail system scenario, residential and commercial development concentrates along proposed stations. This is particularly notorious in bordering areas between Bogota and the municipalities.

In scenarios with the natural reserved open for development (scenarios 3 and 4) the influence of transport infrastructure in land patterns are very similar to those described for scenarios 1 and 2. However, the additional land availability in the North creates a concentration of medium income inside Bogota while at the same time promoting low-income development in the outskirt of the urban area. This result suggests a pattern already occurring in Bogota where low income population are forced to live in high densities locations far from the center. As new transport infrastructures are created, land values increases whereas land for low income is further out. In order to develop a decision support information system and identify differences between all four maps, the circles of mobility (figure 3) were produced for all scenarios. They are intended to support the understanding of implications, in terms of sustainability indicators, of each scenario.



Scenario No.1 - Highway development & VDHR Restricted

Scenario No.2 - Train & VDHR Restricted

Scenario No.3 - Highway development & VDHR Unrestricted

Scenario No.4 - Train & VDHR Unrestricted

Figure 3: Circles of mobility for all 4 scenarios.

Scenarios 1 and 2 show notable differences. Average distance to downtown changes in approximately 1% making it to change of level in the circle. Access rate for commercial land-use changes in 2% creating the same effect in the circle.

On the other hand, Scenario 3, compared to Scenario 2, shows significant changes. Average distance to downtown changes in approximately 1% making it to change of level in the circle. Access rate for commercial land-use changes in 10% changing in one level of the circle.

Concerning the others indicators, they remain in the same rates across all scenarios. Expansion of urban areas, landslide risk and torrential rain risk are in all scenarios between 90% and 100%. Average distance to work, average distance to significant parklands and flood risk are between 60% and 80% in all scenarios. However, average distance to public transport remains lower than 30% in all four scenarios.

Changes between scenarios 1 and 2 are at first in terms on average distance to downtown. The average distance is lower with a highway scenario where more residential land-use is developed near the city; therefore train-based scenario promotes development towards near municipalities. As commercial land-use tends to allocate near new roads, increase in this land-use was likely to happen in scenario 1.

However, comparison between scenario 3 and 4 indicates major changes. New development of commercial land-use is higher in scenario 3 because of the unrestricted reserve. With VDHR unrestricted, residential land-use tends to allocate in the new unrestricted area while the commercial land-use tends to allocate where low income residential were. Average distance to downtown increases also due to the housing process in the reserve.

As location and type of transport infrastructure varies in each of the scenarios, changes produced are different. Table 5 shows total area for each land-use type in the baseline year (2014) and for the forecast year (2040).

As expected in this matrix, most of the new development occurs by the conversion of available land uses (both agricultural and land reserved for expansion). According to the model, 3121 hectares of agricultural land would be converted into urban areas.

Table 5: Contingency table resulted from cross tabulation of 2014 and 2040 (scenario 1) land-use maps (hectares).

Land Use	AFC	Agricul.	High Res.	Med. Res.	Low Res.	Comer.	Indus.	Other	U. Faci.	Roads	W. Bodies	Wetland	2014
AFC	60264	77	120	2711	2318	587	3434	0	0	0	0	0	69511
Agricul.	0	23859	61	2357	1489	343	2763	0	0	0	0	0	30872
High Res.	0	211	1047	36	25	21	19	0	0	0	0	0	1359
Med. Res.	0	1416	300	9775	17	8	91	0	0	0	0	0	11607
Low Res.	0	723	13	3230	2966	1014	3	0	0	0	0	0	7949
Comer.	345	3	154	310	0	331	3	0	0	0	0	0	1146
Indus.	0	768	9	1459	0	191	3206	0	0	0	0	0	5633
Other	0	0	0	0	0	0	0	3162	0	0	0	0	3162
U. Faci.	0	0	0	0	0	0	0	0	2340	0	0	0	2340
Roads	0	0	0	0	0	0	0	0	0	13628	0	0	13628
W. Bodies	0	0	0	0	0	0	0	0	0	0	6784	0	6784
Wetland	0	0	0	0	0	0	0	0	0	0	0	1497	1497
2040	60609	27057	1704	19878	6815	2495	9519	3162	2340	13628	6784	1497	155488

The model results also suggest that the current trend of conversion of industrial areas, particularly close to residential middle income, would continue in the future. In this it is expected that 19 hectares would be transformed from 2014 to 2040.

It can also be observed a conversion from low income areas into commercial (total of 1014 hectares). This could be explained by neighboring relationship between these two land uses in where commercial is dominant.

4 CONCLUSIONS

This paper has described BoLD, a LUCC model for the city of Bogota based on two alternative public transport scenarios. The main objective was to assist decision-making processes by providing LUCC information based on scenarios.

A spatially-explicit model that can assist on decision-making processes has been developed. Results with four scenarios have shown the capability of presenting technical results in relation to positive and negative effects of proposed transport infrastructure. Additionally, the LUCC model application allowed the incorporation of land management policies such as urbanization of green reserves.

This investigation also developed the ODDS, an advanced spatial methodology that allows calculation of ADDF in a technical manner. ODDS contributes to the improvement of LUCC modeling as it fills a gap in the literature in where the influence of accessibility was in many cases modeled using empirical experiences.

The geospatial analyses ODDS appear to be a viable option for practitioners when LUCC simulations are being developed for scenarios based on transport infrastructure proposals. Additionally, the circle of mobility graphical representation also contributes to facilitate decision-making.

Results from different scenarios reflect the differentiation of a highway and a train-based scenario in Bogotá. Indicators reflect in the different circles of mobility that highways promoted the allocation of residential land-use. The majority of indicators were based on distance calculations. Having the VDHR unrestricted allows residential land-use to allocate there while commercial tend to occupy low-income residential areas.

Limitations to the study have been highlighted throughout the text. They can be summarized in two areas:

- We have assumed effects on land-use changes from a particular transport infrastructure are isolated to other transport projects. Although this assumption allows for a clearer differentiation between options, possible synergies between transport alternatives are not considered.
- Practitioners should approach LUCC simulations that only consider transport changes with caution, as they provide a narrow view of future scenarios without clearly considering important aspects such as changes in land demands.

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