ORIGINAL ARTICLE

QUANTIFYING LINEAR URBAN SPRAWL THROUGH OPEN SPACE FRAGMENTATION INDEX: EVIDENCE FROM THE TOMOHON–SONDER PERI- URBAN CORRIDOR, INDONESIA

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ABSTRACT
Urban sprawl is characterized by the horizontal expansion of urban areas, which puts pressure on natural resources, increases land consumption, and increases the need for infrastructure investment and maintenance. One key attribute used to explain this phenomenon is the fragmentation of open space due to uncontrolled urban growth. Therefore, city governments need to monitor trends in urban sprawl to formulate anticipatory strategies to address its consequences. This study explores the use of regression analysis to interpret linear urban sprawl in a peri-urban corridor using a simple open space fragmentation index (the ratio of open space to built-up land) as an indicator. This analysis focuses on the variation of the open space fragmentation index based on the relative distance from the point of origin of urban growth. This case study was conducted in an urban corridor in Tomohon City, North Sulawesi, Indonesia. The results demonstrate that this approach is effective in verifying and interpreting the phenomenon of urban sprawl and has the potential to provide useful feedback for local governments.
Keywords: Geographic Information Systems; Linear Urban Sprawl; Open Space Fragmentation; Peri-Urban Corridor; Spatial Planning.

INTRODUCTION

Urban sprawl has long been recognized as one of the major challenges in contemporary urban development because it contradicts the compact city ideal and often generates environmental, spatial, and infrastructural inefficiencies. Generally, sprawling cities are characterized by low-density horizontal expansion, dispersed urban morphology, and increasing land conversion for urban purposes, all of which place pressure on natural resources and ecological carrying capacity (Artmann et al., 2019; Güneralp et al., 2020). In many cases, sprawling urban structures also develop polycentrically, resulting in greater average distances between activity zones and increasing dependence on transportation infrastructure and motorized mobility, reinforcing automobile-oriented urban structures and commuting inefficiencies (Raimbault, 2021), with consequent impacts on air quality and public health (Bertaud & Richardson, 2004; Gao et al., 2019; Johnson, 2001). Nevertheless, urban sprawl is not exclusively interpreted negatively. In some contexts, it is associated with suburbanization and economic decentralization, representing the outward redistribution of urban activities from central areas toward peripheral zones (Divigalpitiya & Handayani, 2015), which in many developing regions is increasingly associated with peri-urban transformation and metropolitan restructuring. Theoretical perspectives on urban sprawl also vary considerably. Setioko (2009) defines it as scattered, unplanned, low-density, and unstructured urban growth, while Soetomo (2013) interprets it as a horizontal urbanization process contributing to the formation of mega-urban regions. Bento et al. (2006) further argue that sprawling development reflects inefficient urban growth driven by increasing housing demand, rising land values, and weak governmental control.

The spatial manifestation of urban sprawl itself can take multiple forms. Yunus (2008) categorizes urban expansion into concentric, linear, and leapfrog patterns, while also emphasizing the influence of accessibility, public service availability, land characteristics, ownership structures, spatial regulations, and developer initiatives on centrifugal urban growth. Among these forms, linear sprawl or ribbon development is particularly significant because transportation corridors often function as catalysts for fragmented and incremental urban expansion. However, despite the growing concern regarding sprawling urbanization, the phenomenon is often insufficiently anticipated within urban governance practices. In many cases, urban development policies unintentionally accelerate sprawling growth patterns without adequate monitoring instruments. Consequently, urban authorities require effective approaches capable of identifying and measuring sprawl dynamics particularly in rapidly urbanizing regions where land-use transitions occur faster than planning adaptation mechanisms (UN-Habitat, 2020). Herold et al. (2005) emphasize that the measurement of urban form can function as an important instrument for evaluating the effectiveness of urban growth control policies.

Various methods for measuring urban sprawl have been developed over time, ranging from density-based indicators to sophisticated geospatial and landscape analyses. Recent developments increasingly integrate remote sensing, machine learning, and geospatial big data approaches into urban growth analysis (Li et al., 2021; Van Etten et al., 2021). Huang et al. (2020), for example, utilized a deep learning fusion neural network algorithm to quantify urban sprawl, while Lowry et al. (2014) compared eighteen urban form metrics across hundreds of neighborhoods to examine their ability to describe urban morphology. Manesha et al. (2021) integrated expansion intensity indices, Shannon entropy, and landscape metrics, whereas Shi et al. (2023) employed both single and composite indices derived from multi-source geospatial datasets. Density itself has consistently been regarded as one of the most important indicators of urban form because it strongly influences urban efficiency, accessibility, and environmental performance (OECD, 2018). Churchman (1999) identifies density as the most intuitive variable for representing urban structure, while Galster et al. (2001) argue that sprawl corresponds to the lowest values of variables such as population density, road connectivity, building clustering, land-use mix, and proximity to urban centers. Other studies have proposed additional measurement approaches, including classifications based on density, land-use heterogeneity, and spatial structure patterns which are increasingly analyzed through landscape ecological and spatial morphology frameworks (Liu et al., 2018; Tsai, 2005), as well as indicators related to building density, accessibility, mixed-use proximity, and leapfrog development characteristics (Ewing et al., 2015; Hasse & Richard, 2003).

Despite the diversity of existing approaches, relatively limited attention has been given to the measurement of linear sprawl at corridor scales, particularly through the perspective of green open space fragmentation. Burchfield et al. (2005) define sprawl through the proportion of undeveloped land surrounding urban dwellings, while Angel et al. (2007) identify open space fragmentation as one of the essential attributes of urban sprawl. Recent studies also demonstrate that fragmentation significantly affects ecosystem services, spatial connectivity, and urban resilience (Hersperger et al., 2018). Verbeek and Tempels (2016) emphasize fragmentation analysis as a key approach for understanding sprawling urban dynamics. Nevertheless, many existing methods remain relatively complex and are often difficult to apply, particularly for corridor-scale monitoring in medium-sized cities within developing countries. Therefore, this study aims to develop a relatively simple and applicable method for indexing the intensity of linear urban sprawl based on green open space fragmentation along major road corridors. The method is tested through a case study in Tomohon City, Indonesia, an urban area characterized by prominent ribbon development patterns due to its strategic position along arterial routes connecting several major cities in North Sulawesi. By proposing a corridor-oriented fragmentation index, this research seeks to contribute both theoretically and practically to the development of urban sprawl measurement methods and to support more responsive spatial planning and urban growth management.

METHOD

This research was designed to involve several structured stages to ensure academically sound results. These stages are formulated as follows.

1) Theoretical Review as a Methodological Foundation
   The initial stage of the research focused on exploring relevant literature on the phenomenon of urban sprawl, with particular attention to quantification methods used in various previous studies. The literature review was conducted comprehensively, encompassing books, journal articles, and other credible scientific sources. The results of this theoretical review served as a conceptual reference and foundation for formulating the proposed indexing method, with an emphasis on linear sprawl intensity. Therefore, this stage also served as the first data point, providing the research's analytical framework.
2) Formulation of the Linear Sprawl Quantification Method
   Based on the theoretical interpretation results from the first stage, the research team designed a method for quantifying linear sprawl intensity. This method formulation was implemented in the

form of a systematic analytical procedure, complete with a description of input data requirements. This formulation emphasizes the fragmentation of open space as a key attribute of the sprawl phenomenon, with the limitation that development only encompasses linear forms that typically follow main road corridors from the city center to the outskirts.

3) Simulation Application in Case Studies
The next stage was testing the method through simulations in Tomohon City, which was chosen as the case study location because it exhibits clear linear sprawl symptoms. Urban physical data obtained from this area served as a second data point to test the method's ability to measure sprawl intensity on main road corridors. This simulation was expected to generate a linear sprawl index value that would allow for comparisons between corridor segments.
4) Interpretation and Analysis of Results
Once the index was obtained, the fourth stage focused on interpreting the simulation results. Analysis was conducted to assess the extent to which the applied quantification method was able to represent differences in sprawl intensity between corridors. This process also aimed to identify factors influencing variations in index values. In this stage, a third data point was used: information on the general condition of Tomohon City, both physical and non-physical. The interpretation was qualitative and quantitative, linking the index values to the existing local context.
5) Drawing Conclusions and Recommendations
The final stage is formulating research conclusions aligned with the objectives and problem formulation. Based on the analysis, strategic recommendations are developed for further research development and for sprawl control practices in the field. These recommendations are expected to provide added value to spatial planning and management and to yield a more accurate understanding of urban sprawl dynamics.

The linear sprawl quantification method developed in this study is based on the open space fragmentation attribute. The operational steps formulated are as follows:

1) Determining Observation Locations
The observation zone focused on the main road corridor connecting the Central Business District (CBD) with the suburbs and other areas outside the city.
2) Application of Buffering Techniques
The selected road corridor was then given a 100-meter buffer on the left and right sides of the road. Delineative mapping was conducted in this area to differentiate built-up land from open space. The results were visualized in the form of a thematic map.
3) Dividing the Area into Blocks
The delineated area was divided into several blocks, each 200 meters long, for each road segment. The area of each block was set at 200 x 200 meters (40,000 m^2 or 4 ha). The blocks were numbered from the closest to the CBD to the outskirts of the city. A thematic map was created to demonstrate this division.
4) Area Calculation and Fragmentation Index
For each block, the built-up area and open space were calculated, which were then presented in a table. The Open Space Fragmentation Index was calculated by comparing the percentage of open space to the percentage of built-up land.
5) Trend Analysis
The analysis was conducted by utilizing the correlation between the block's relative distance from the CBD and three dependent variables: the percentage of built-up land, the percentage of open space, and the fragmentation index. The data relationships were visualized in a scatter plot, complemented by a regression equation to identify patterns.
6) Interpretation of Results
Interpretation was performed on the emerging trend pattern. If the trend is linear, this indicates a tendency for slowing sprawl and increasing urban compactness, indicating that a zone is approaching a fragmentation saturation point. Conversely, a nonlinear trend indicates that open space fragmentation is still intense. In addition to the trend pattern, the form of the regression equation provides information regarding the effect of block distance on variations in built-up land and open space. Theoretical assumptions state that the farther from the city center, the percentage of built-up land decreases, while open space and the fragmentation index increase. Patterns that deviate from

these assumptions can be considered anomalies caused by external factors. The coefficient of determination from the regression equation was also analyzed to determine the contribution of distance to sprawl intensity in the studied corridor.

Through this methodology, the study seeks to develop a simple yet applicable framework for assessing linear sprawl intensity in urban road corridors. The steps taken allow not only quantitative measurements but also contextual interpretations that enrich understanding of the dynamics of urban spatial development

RESULTS AND DISCUSSION

The results are interpreted in relation to the two earlier Mapanget studies. The cellular-automata analysis by Sela, Malik, Tilaar, and Lestari (2024) identified strong future settlement pressure associated with existing settlements and infrastructure corridors. The land-use study by Sela, Malik, Tilaar, Simulation of the application of the sprawl quantification method in Tomohon City requires two main types of data, namely general data on the city as the study area and spatial data related to the fragmentation of open space and the distribution of built-up land in the observation corridor. Tomohon City is located approximately 23 km from Manado, the capital of North Sulawesi Province, at 1°15' N and 124°50' E, with an elevation of 900–1100 meters above sea level. Administratively, the city comprises 44 villages within 5 sub-districts, covering an area of 147.22 km² (14,721.78 ha). Its status as an autonomous city contributes to regional dynamics and accelerates development in North Sulawesi. In recent years, Tomohon has experienced rapid growth, marked by the emergence of various new businesses, increased population mobility, and migration. The local economy is dominated by agriculture, particularly vegetable and flower production, complemented by the knock-down wooden housing industry. Furthermore, Tomohon is a leading tourist destination in North Sulawesi thanks to its cool climate, mountainous landscape, and diverse nature-based attractions.

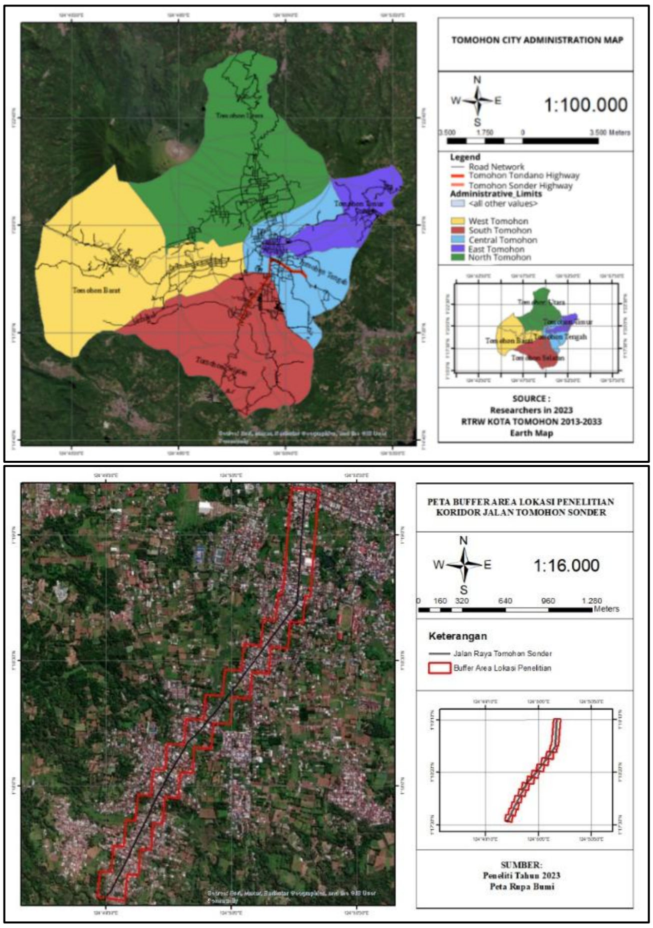

Figure 1. Administrative Map of Tomohon City & Delineation of the Case Study Area
Source: Processed Data by Research Team

In accordance with the established methodology, the initial stage of the simulation was to determine the observation location for the sprawl phenomenon. This study selected the road corridor connecting Tomohon City with the Sonder urban area in Minahasa Regency (the Tomohon–Sonder Corridor) as the object of study. A thematic map delineating the case study area was displayed to clarify the area's boundaries. The study area was located in South Tomohon District, starting from the main intersection of Jalan Sam Ratulangi–Jalan Raya Tomohon (the location of the Opo/Dotu Tololiu Tua Statue) to the city border area in Sarongsong and Tumatangtang Villages, which is characterized by the conversion of urban land to plantations.

The delineation results indicate that the case study area has a total area of 640,000 m² (64 hectares). The thematic map shows the block division and the distribution of built-up land. This process resulted in 16 blocks with an average area of 4 hectares, each with proportion of the built-up land and open space area as listed in Table 1.

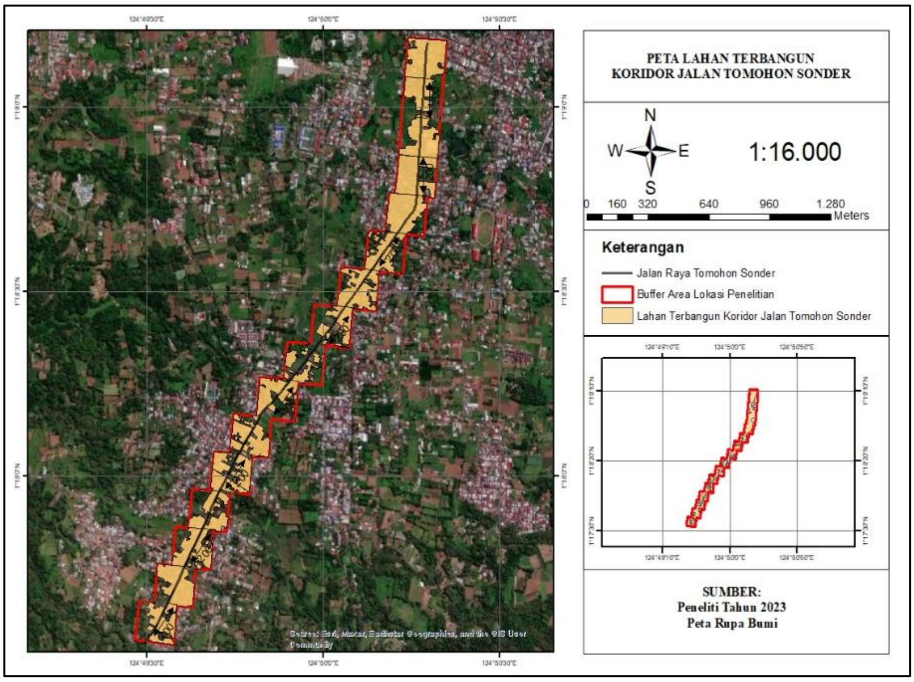

Figure 2. Distribution of Blocks and Plots of Built-up Land in the Case Study Area
Source: Processed Data by Research Team

Table 1. Sprawl Data Quantification Results Per Block in the Case Study Area

Block	Block Area M^2	Built-up Land Area		Open Space Area	
		M^2	%	M^2	%
1	40.000	35.801	89,50	4.199	10,50
2	40.000	20.448	51,12	19.552	48,88
3	40.000	28.240	70,60	11.760	29,40
4	40.000	32.436	81,09	7.564	18,91
5	40.000	32.710	81,78	7.290	18,23
6	40.000	24.175	60,44	15.825	39,56
7	40.000	32.205	80,51	7.795	19,49
8	40.000	18.752	46,88	21.248	53,12
9	40.000	13.657	34,14	26.343	65,86
10	40.000	24.173	60,43	15.827	39,57
11	40.000	26.462	66,16	13.538	33,85

12	40.000	31.343	78,36	8.657	21,64
13	40.000	21.304	53,26	18.696	46,74
14	40.000	26.890	67,23	13.110	32,78
15	40.000	29.326	73,32	10.674	26,69
16	40.000	22.417	56,04	17.583	43,96
Total	640.000	420.339	65,68	219.661	34,32

Source: Processed Data by Research Team

Based on the measurement results and according to the sprawl quantification procedure, trend analyses were conducted by correlating the relative distance of each block from the sprawl origin (independent variable, X) with the percentage of built-up land, the percentage of open space, and the open space fragmentation index per block (dependent variables, Y1, Y2, Y3). Table 2 presents the input data used in the trend analysis.

Table 2. Input Data for Sprawl Trend Analysis Based on Relative Distance to Origin Point

Block	X Relative Distance to Origin (M)	Y1 Built-up Land Area (%)	Y2 Open Space Area (%)	Y3 Open Space Fragmentation Index (Y1 / Y2)
1	100	89,50	10,50	0,12
2	300	51,12	48,88	0,96
3	500	70,60	29,40	0,42
4	700	81,09	18,91	0,23
5	900	81,78	18,23	0,22
6	1.100	60,44	39,56	0,65
7	1.300	80,51	19,49	0,24
8	1.500	46,88	53,12	1,13
9	1.700	34,14	65,86	1,93
10	1.900	60,43	39,57	0,65
11	2.100	66,16	33,85	0,51
12	2.300	78,36	21,64	0,28
13	2.500	53,26	46,74	0,88
14	2.700	67,23	32,78	0,49
15	2.900	73,32	26,69	0,36
16	3.100	56,04	43,96	0,78

Source: Processed Data by Research Team

The input data is also visualized in Figure 3, which displays the proportion of built-up land and open space per block based on the relative distance from the corridor origin. This visualization shows the variation in the proportion of open space in each block according to its relative position to the growth center.

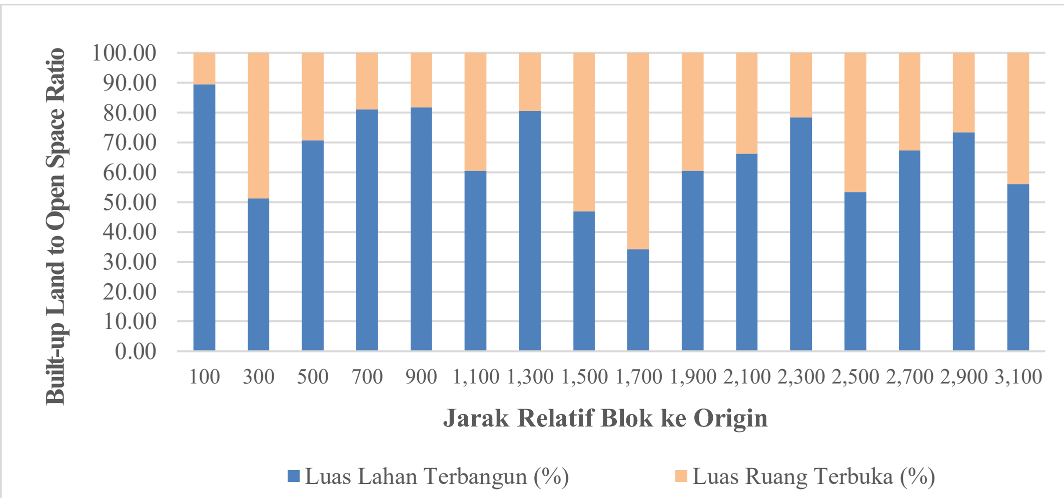

Figure 3. Proportion of Built-up Land and Open Space per Block by Distance
Source: Processed Data by Research Team

Based on the input data, the analysis continued with the preparation of scatterplots using MS Excel to map the relationship between the independent variable (X) and the dependent variable (Y1, Y2, Y3) separately. Each diagram is equipped with a trendline as well as a regression equation and coefficient of determination value, with the trend selection based on the strength of the coefficient of determination. As a result, three diagrams are presented to illustrate the relationship between X–Y1, X–Y2, and X–Y3.

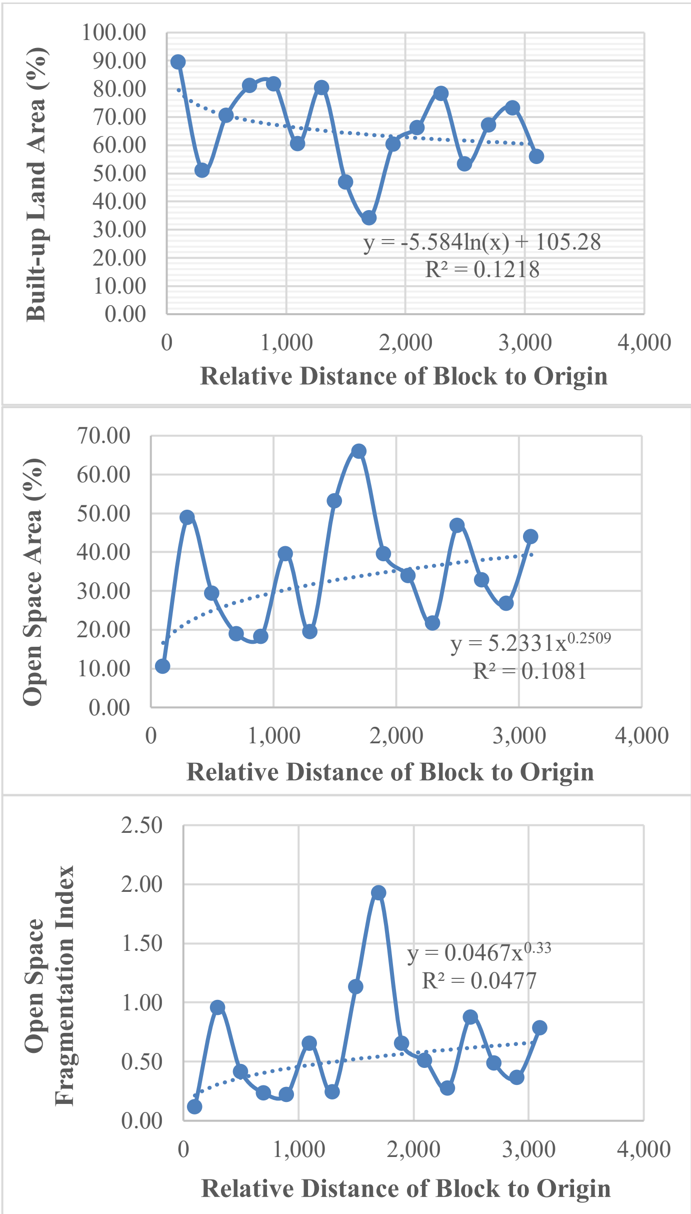

Figure 4. Scatterplot and Sprawl Trends Based on Relative Distance to the Point of Origin
Source: Analyses Results by Research Team

Referring to the previously formulated method, the sprawl phenomenon in the graph can be interpreted using several approaches.

1) Interpretation based on trend type.

   The scatterplot between the open space fragmentation index and the relative distance of blocks from the origin shows a non-linear power trend. This indicates that sprawl in the corridor has not yet reached saturation, although some blocks already have nearly 100% built-up land cover, reflecting increasing compactness. The fact that several other blocks still show a low proportion of built-up land and a high fragmentation index (even >1) indicates that open space in these blocks still predominates over built-up land.

2) Interpretation based on the form of the regression equation and trend line
The regression equation in the scatterplot indicates a consistent causal relationship between the independent variable (X) and the dependent variables (Y1, Y2, Y3). The first graph shows a negative logarithmic relationship, where increasing distance from the origin (X) correlates with a decreasing percentage of built-up land (Y1). Conversely, the second graph shows a positive correlation, where the further the distance from the origin, the greater the proportion of open space (Y2). A similar pattern is also seen in the third graph, where increasing distance correlates with an increase in the open space fragmentation index (Y3).
3) Interpretation based on the coefficient of determination
The regression coefficient of determination in all three graphs is relatively low, ranging from 0.12–0.23, indicating a weak influence of the distance variable (X) on the percentage of built-up land (Y1), open space (Y2), and the fragmentation index (Y3). This suggests that other factors are more dominant in determining the variation in these three variables. Based on the corridor image, factors suspected to be influential include local road networks paralleling or intersecting main routes, as well as the presence of agricultural land, plantations, and water bodies. In general, blocks with local road networks tend to have high built-up land cover and low open space, while blocks with agricultural or water functions show the opposite.
4) Interpretation based on the shape of the graph curves

The scatter plot curve in the second case shows dynamic fluctuations, with a downward trend in the first graph and an increase in the second and third. This pattern confirms that open space fragmentation is still ongoing and that sprawl has not yet reached saturation. If saturated, the open space in each block will be completely replaced by built-up land so that the corridor displays a high level of urban compactness, accompanied by an increase in building footprint ration and a tendency for vertical growth that drives an increase in floor area ratio

CONCLUSION

Quantifying the intensity of urban expansion in an urban corridor can be done by calculating the Open Space Fragmentation Index in a number of delineated blocks along the observed road corridor. Block delineation can be done by creating a buffer area along the corridor with a width of 100 meters on the left and right of the road lane, and segmenting blocks per 200 meters of the observed corridor road lane. Mathematically, the open space fragmentation index for each block can be calculated as the ratio between the total area or percentage of open space to the total area or percentage of built-up land area for each block. The index value will range from "0" (if the block is entirely built-up land) to "∞" (if the block is entirely open space). A higher open space fragmentation index indicates a higher intensity of open space fragmentation and urban expansion in the observed corridor. An index value > 1 indicates that the proportion of open space is more dominant than the built-up land area in the observed corridor. Interpretation of linear sprawl in a particular urban corridor can be done by visualizing the relationship between the open space fragmentation index of each block and the distance of each block from the origin in the form of a scatter plot and observing the regression trend. A trend that tends toward linearity indicates sprawl conditions that are heading toward saturation, while a trend that tends toward non-linearity indicates still-intense sprawl conditions.

Simulations of this quantification/indexation method, using a case study in Tomohon City, demonstrate the linear sprawl phenomenon that occurs, which can be briefly described as follows.

1) The open space fragmentation index, with a value of 0.52, indicates a relatively low level of sprawl intensity, shifting toward the urban compactness attribute, indicating that built-up land tends to be more dominant in the area.
2) The regression trend characteristics of the open space fragmentation index on the relative distance of blocks from the origin in this case study tend to be non-linear and indicate that linear sprawl phenomena in both corridors persist, in line with the open space fragmentation index values that tend to increase with increasing distance from the origin and closer to the suburbs.

3) The regression trend characteristics in this case also show a relatively low coefficient of determination, indicating that the relative distance of blocks from the origin is not actually significant enough as a determining factor in the value of the open space fragmentation index for each block, and that several other factors must be involved in determining the intensity of sprawl that occurs.

The following are some suggestions, particularly regarding efforts to improve the quality of sprawl quantification or indexing methods and the interpretation of simulation results from these methods in different cases.

1) The quality of buffering techniques in block delineation can be improved by referring to the actual boundaries of land parcels along the observation corridor based on the availability of control and/or ownership data.
2) Development of a regression trend index for open space fragmentation, which can be expanded to include a number of other independent variables (in addition to the relative distance of the block to the origin), preceded by a rationale study to determine whether these new variables influence sprawl intensity. Other variables that can be considered include the presence of intersections or parallels with local road routes, applicable land use guidelines or regulations, etc.

Simulation methods for corridors as case studies should also be conducted comparatively within the framework of variations in the state of the open space fragmentation index over time within the same corridor

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