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Land Use Dynamics and Rural-urban Transformation of Kedungsepur Metropolitan Area in Central Java Province, Indonesia

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ABSTRACT

Urbanization represents a dominant worldwide phenomenon that increasingly transforms spatial system and ecological conditions across regions. The Kedungsepur Metropolitan area in Central Java Province, Indonesia, comprises Kendal, Demak, Ungaran (Semarang Regency), Semarang City, Salatiga, and Purwodadi (Grobogan) and represents one of the country's rapidly developing metropolitan regions. This metropolitan area provides a representative case for examining how urbanization shapes land use transitions, spatial clustering, and sustainability disparities within an underexplored integrative metropolitan perspective. This study aims to quantify land use and land cover (LUCC) change and assess rural-urban transformation. This study applies a gain-loss analysis to assess LULC dynamics, employs the rural urban index (RUI), uses spatial autocorrelation index (Moran's I and Local Indicator for Spatial Association/LISA). Based on the LUCC analysis, extensive forest conversion to dryland agriculture and built-up areas occurred, totaling 64,739.09 ha, while the number of urban villages increased from 235 to 302 between 2012 and 2022. Kendal experienced the highest level of urban transformation (31%), whereas Salatiga and Grobogan showed minimal change (6%). A Moran's I value of 0.83 indicates a strong spatial clustering of urban growth. The findings highlight the need of integrated spatial planning and strengthened urban-rural transformation as key strategies for achieve sustainable regional development.

Introduction

Urbanization represents a dominant global phenomenon and a major driver of spatial and socioeconomic change, increasingly transforming spatial systems, land-use dynamics, ecological conditions, environmental sustainability, and regional inequality [1]. In Indonesia, these dynamics are particularly evident on Java Island, especially in the Kedungsepur Metropolitan Area in Central Java Province. This area that comprises Kendal, Demak, Ungaran (Semarang Regency), Semarang City, Salatiga, and Purwodadi (Grobogan) designated as center of national strategic growth under Presidential Regulation No. 78/2017 concerning the Spatial Plan for the Kendal, Demak, Ungaran, Salatiga, Semarang, and Purwodadi Urban Areas. Kedungsepur serves a major economic and logistics hub in Central Java, underpinned by strategic connectivity trough Pantura (*Pantai Utara Jawa*/North Coast of Java) corridor, Trans Java toll road network, railway stations, Ahmad Yani International airport, and Port of Tanjung Mas [2]. Its advantageous geographic position has accelerated urbanization and industrial development and drives significant land use and land cover (LULC) changes, particularly forest and agricultural land conversation to build-up areas [3].

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This metropolitan area provides a representative case for examining how urbanization shapes land use transitions and spatial clustering within an underexplored metropolitan perspective. This urbanization process increases the pressure on natural resource, including degraded ecosystem, increased water and energy demand, accumulated waste, and declined of biodiversity. These pressures contribute to local impacts such as flood hazard, land subsidence, and habitat fragmentation, while also contributing global impacts such as climate change. Empirical evidence from rapidly urbanizing areas highlights that urban expansion often declines ecosystem services and ecological integrity [4,5]. At the micro or local scale, infrastructure development has progressed faster than spatial planning regulations, resulting in uneven and environmentally unsustainable growth patterns [6,7]. Collectively, these conditions highlight the critical need for adaptive and integrated management approaches to promote sustainable resource use and safeguard ecological integrity in rapidly urbanization [8,9].

Although numerous studies have examined urbanization and LULC changes in metropolitan regions of Java [10,11], most have concentrated on physical LULC changes while giving limited attention to the interactions between social, economic, and ecological dimensions. To bridge this gap, this research develops a comprehension Rural-Urban Index (RUI) that incorporates both ecological and social indicators. Spatial patterns of urbanizations are analysed using Global Moran's Index (Moran's I) and Local Indicators of Spatial Association (LISA) to identify spatial clustering.

Based on previous research problem and gaps, this study aims to quantify LUCC change and assess rural-urban transformation in the Kedungsepur Area. The findings of this study are expected to support balanced development strategies, enhance urban-rural relationship, and contribute to evidence-based policymaking for sustainable management in Kedungsepur. By integrating sustainability assessment and spatial analysis, this research addresses the limitations of previous studies that focused mainly on physical LULC change and offers practical insights for regional planning and natural resources management.

Materials and Methods

Research Location

This research was carried out in the Kedungsepur Metropolitan Area located in Central Java Province, Java Island, Indonesia. Kedungsepur is one of seven development areas in Central Java Province, consisting of four regencies and two cities, namely Kendal Regency, Demak Regency, Semarang Regency (Ungaran), Salatiga City, Semarang City, and Grobogan Regency (Purwodadi). The total area of Kedungsepur is 534,077.70 hectares, which is approximately 16.4 percent of the total area of Central Java Province [12]. Astronomically Kedungsepur is located at 109°10'–111°25' E, and 6°43'26''–7°32' S, while geographically the Kedungsepur WP is bordered by the following areas: The north is bordered by Jepara Regency and the Java Sea; the east is bordered by Temanggung Regency, Boyolali Regency, Sragen Regency, and Magelang Regency; the south is bordered by Kudus Regency, Pati Regency, and Blora Regency; Batang Regency borders the west. The research location is presented in Figure 1.

Tools and Materials

This study used primary and secondary data. The primary data consisted of field checking data, questionnaires filled out by several resource persons, and key person interviews. The secondary data used included land use data at a scale of 1:250,000, topographic maps of Indonesia, village potential data, and the Shuttle Radar Topographic Mission (SRTM) 1 Arc-Second Global Digital Elevation Model (DEM), as well as infrastructure data obtained from several related agencies such as *Kementerian Lingkungan Hidup dan Kehutanan* (KLHK), *Badan Pusat Statistik* (BPS), and Badan Informasi Geospasial (BIG) [13]. The types and sources of data used are presented in Table 1. The tools used included the Global Positioning System (GPS), compass, map of the research area, laptop, geographic information system software (ArcGIS and QGIS), statistical processing software (Statistica and SPSS, and GeoDa).

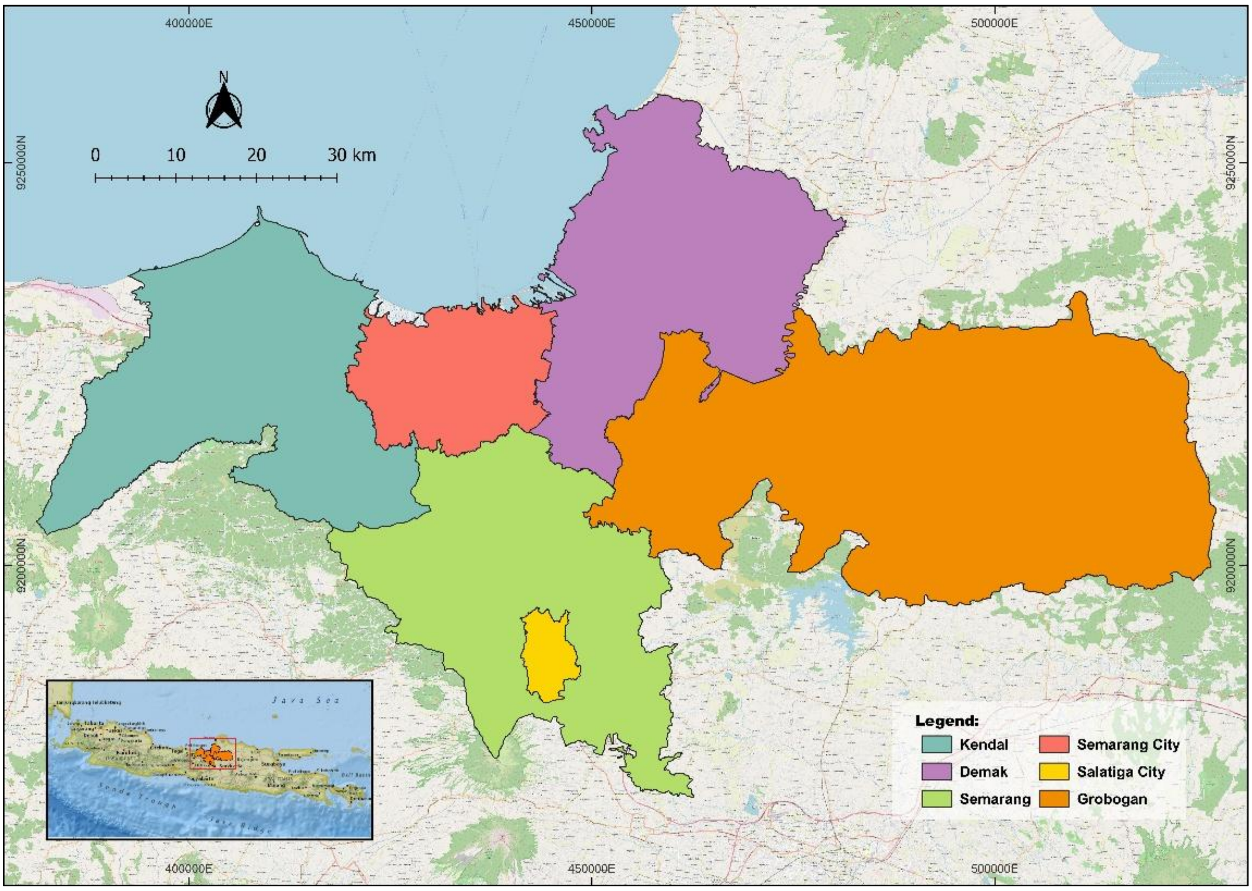

Figure 1. Kedungsepur Metropolitan Area in Central Java, Indonesia. The figure shows the geographical location and spatial distribution of the administrative units forming the Kedungsepur Metropolitan Area, which consist of four regencies and two cities.

Table 1. Description of data types, forms, and sources for analysis. This table summarizes eight groups of data employed in the study, including various spatial and non-spatial data formats obtained from primary and secondary source through official data provider.

No.	Data type	Data form	Source
Primary data			
1.	Ground check point	Tabular	Field
2.	Parameter weight assessment RUI	Tabular	Respondents
3.	Key person interview	Textual	Respondents
Secondary data			
1.	Land use map at a scale of 1:250,000	Map	KLHK
2.	Topographic map (RBI)	Map	BIG
3.	Village potential data (Podes)	Tabular	BPS
4.	Digital Elevation Model (DEM)	Map	USGS (United States Geological Survey)
5.	Infrastructure data	Map	Central Java Regional Government

Data Collection

The expert survey method was used to gather opinions or information from experts as a basis for determining the weights of each RUI analysis parameter. An expert-based survey was employed as a comprehensive review, drawing on insights from experts across multiple disciplines to capture a multidimensional stakeholder perspective [14]. Respondents were selected using purposive sampling, whereby individuals were deliberately chosen based on criteria aligned with the research objectives. These criteria included: 1) Demonstrated experience and expertise in the relevant field, 2) Positions and professional standing that indicate credibility, and 3) Willingness and consistency in participating as respondents. The selected experts were classified into three groups, namely academics/lecturer, researchers, and government agencies, to reflect and compare differing perspectives among key decision-makers. A total of six experts participated in the study, with two representatives from each category.

Data Analysis

Multitemporal land sue data for 2012 and 2022 obtained from KLHK were used to analyse LULC change using overlay and reclassification techniques. Data processing involved several steps: 1) Clipping LULC datasets to the Kedungsepur Metropolitan Area boundaries, 2) Aggregating detailed LULC classes into seven major land use classes (Table 2) [15,16], 3) Calculating the area and proportion of each land use class across the metropolitan area, and 4) Identifying LULC change pattern using a gain-loss approach to quantify increases and decreases in LULC between 2012 and 2022 [17,18]. This method enabled consistent identification of dominant LULC transitions while acknowledging inherent uncertainties in the data. Although KLHK provides nationally consistent LULC coverage, potential classification errors and temporal inconsistencies may exist. Therefore, the analysis emphasizes major transitions at the metropolitan scale to ensure robustness and clarity LULC change trends.

Table 2. Aggregate land use classes and description. This table describes the land use/land cover classes applied in the analysis, including the characteristics and classification boundaries of each class.

Class	Description
Waterbodies	Rivers, lakes, swamps, open water, reservoirs, and ponds
Forest/Vegetation	Dryland forest (primary and secondary), industrial plantation forest, mangrove forest (primary and secondary), swamp forest
Plantation	Plantation area
Dryland agriculture	Dryland agriculture and mixed dryland agriculture
Rice field	Rice field area
Built-up land	Settlements, airports, ports, and industrial areas
Others	Scrub, swamp bushes, and open land

Rural-urban areas in this study were identified using an enhanced RUI approach. Rural-urban interactions are understood as multidimensional and reciprocal linkages between rural and urban areas, encompassing flow of people, goods, services, information, and capital. These interactions play a critical role in driving spatial transformation, particularly in metropolitan regions that are functionally interconnected with surrounding rural areas. In the context of this study, Kedungsepur provides an appropriate case study, as its rural hinterlands both shape and respond to dynamics within the urban core.

To examine rural-urban transformation, this study developed an improved RUI that moves beyond a conventional focus on LULC. This improved RUI integrates physical and socio-economic indicators, such as LULC, population density, accessibility, elevation, slope, and the spatio-temporal distribution of industrial areas, thereby capturing both landscape characteristics and human dimensions [19]. So, this improved RUI can provide a robust basis for evaluating rural-urban transformation and facilitates a deeper understanding of spatial dynamics relevant to sustainable LULC and environmental planning.

Indicator weights where derived using the Analytical Hierarchy Process (AHP) (Figure 2), involving six experts from central government, local government, and academia (Table 3) [20]. The relatively small number of experts reflects the rapid assessment approach, which prioritizes expert judgement over sample size. All respondents processed experience in spatial planning and regional development, ensuring the reliability and contextual relevance of the assigned weights. The weighting process aimed to represent the relative importance of each LULC class, biophysical landscape characteristics, and socio-economy aspect in relation to urbanization. Positive indicators denote compatibility with urban functions, and negative indicators indicate constraints or incompatibility with urban expansion [21].

Quantitative and qualitative validation were employed to ensure the reliability and contextual validity of RUI classification. Quantitative validation involved spatial accuracy assessment and correlation analysis using supporting demographic and infrastructure datasets. On the other hand, qualitative validation was carried out through interviews with key stakeholders from government agencies and academia to evaluate the plausibility of the RUI results. The consistency between expert assessment and RUI results enhances the credibility of the RUI in representing the spatial dynamics of rural-urban transformation in the Kedungsepur.

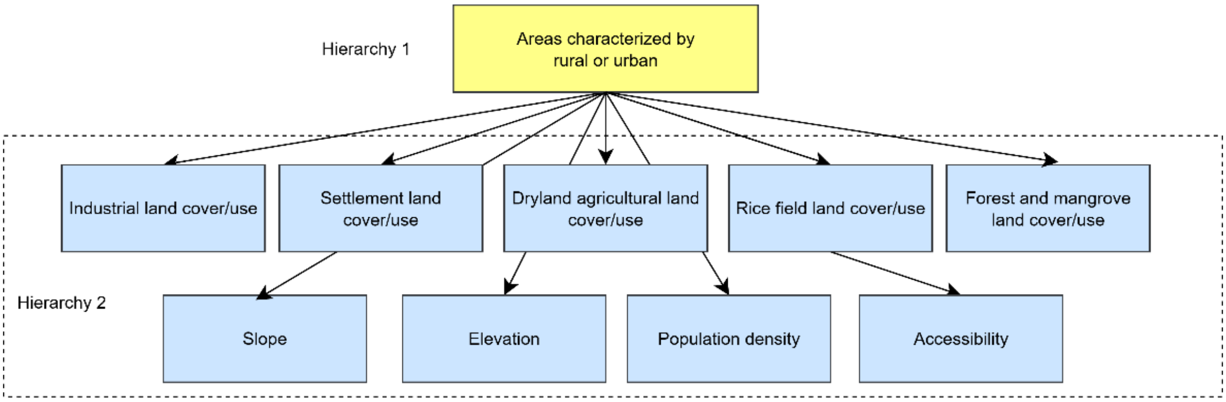

Figure 2. AHP-based weighting of RUI indicators. This diagram illustrates the decision-making structure of the analytical hierarchy process, where hierarchy 1 represents the goal of determining rural-urban characteristics and hierarchy 2 depicts the ten criteria used in the weighting process.

Table 3. Criteria, weights, and direction used in RUI. This table presents the weighting of each criterion determining regional characteristics and its directional influence, where positive value indicate urban tendencies ad negative value indicate rural tendencies.

Code	Criteria description	Weight	Directions
KI	Industrial area	0.200	+
KP	Residential area	0.193	+
LK	Dry/open land	0.046	-
PLB	Wetland farming	0.030	-
HM	Forest and mangrove	0.025	-
KC	Mixed garden	0.031	-
Sp	Slope	0.041	-
At	Elevation	0.041	-
Pd	Population density	0.172	+
Ac	Accessibility	0.221	+

Following the calculation of RUI for each village and sub-district, the results were classified into rural-urban classes using interval-based thresholds (Equation 1). Villages with RUI values close to 0 (RUI ≈ 0) were classified as rural, indicating LULC composition and physical conditions that primarily support rural activities. In contrast, areas with RUI values approaching 1 (RUI ≈ 1) were designated as urban, reflecting the prevalence of land use patterns and environmental characteristics associated with urban development.

$$RUI = \left(\begin{array}{c} \left(\frac{KI}{Total\ Area} \times 0.200\right) + \left(\frac{KP}{Total\ Area} \times 0.193\right) - \\ \left(\frac{LK}{Total\ Area} \times 0.046\right) - \left(\frac{PLB}{Total\ Area} \times 0.030\right) - \left(\frac{HM}{Total\ Area} \times 0.025\right) \\ - \left(\frac{KC}{Total\ Area} \times 0.031\right) - (Sp \times 0.041) - (At \times 0.041) \\ +(Pd \times 0.172) + (Ac \times 0.221) \end{array} \right) \quad (1)$$

Spatial pattern and autocorrelation were analysed using Moran's I (Equation 2) and LISA (Equation 3) to identify the concentration of rural and urban areas across regencies/cities as representation of the spatial pattern of rural-urban transformation in the Kedungsepur [22]. The analysis used the proportion of built-up area at the village level as the primary variable. While Moran's I capture the overall degree of spatial clustering, LISA reveals localized patterns, including high-high and low-low clusters, that indicate varying intensities of urban expansion. High-high clusters commonly located in urban cores and development corridors and reflect concentrated growth that may pose risks to ecological balance and contribute to the reduction of green spaces. Low-low clusters suggest areas with relatively preserved natural land cover.

$$I = \frac{N \sum_{i=1}^{n} \sum_{j=1}^{n} Wij\ (xi-\bar{x})(xj-\bar{x})}{\left(\sum_{i=1}^{n} \sum_{j=1}^{n} Wij\right) \sum_{i=1}^{n} (xi-\bar{x})^2} \quad (2)$$

$$Ii = \frac{n \sum_{j=1}^{n} Wij\ (xi-\bar{x})(xj-\bar{x})}{Z_x^2 \sum_{j=1}^{n} Wij} \quad (3)$$

Results

Land Use and Land Cover Change in Kedungsepur 2012–2022

A study of land use in the Kedungsepur Metropolitan Area was conducted for 2012 and 2022 (Table 4). Rice fields and forests made up the most land cover in 2012, covering more than 65% of the total area. About 35% of the land was rice fields, and about 31% was forests. The remaining area included build-up land, dryland farming, plantations, water bodies, and areas labelled "others". Together, these made up just over one-third of the metropolitan area.

Table 4. LULC classes and changes in Kedungsepur Area for 2012 and 2022. This table presents the area of each land cover class in 2012 and 2022, along with the magnitude of land cover changes over the ten-year periode across the metropolitan area.

Land use class	Area 2012		Area 2022		Area change
	(ha)	(%)	(ha)	(%)	(ha)
Water body	16,358.23	3.06	18,753.98	3.51	2,395.74
Forest	164,100.07	30.73	99,360.98	18.60	–64,739.09
Built-up land	83,911.50	15.71	118,929.15	22.27	35,017.64
Others	17,080.96	3.20	2,158.04	0.40	–14,922.92
Plantantion	11,741.79	2.20	15,480.74	2.90	3,738.95
Dryland agriculture	52,772.03	9.88	98,997.01	18.54	46,224.99
Rice field	188,113.12	35.22	180,397.81	33.78	–7,715.31
Kedungsepur	534,077.70		534,077.70		

The types of land use changed in 2022 (Table 4). Rice fields remained the largest land use, accounting for 33.78% of the total, even though their area shrank by 1,44%. The amount of built-up land rose from 15.71% to 22.27%, and the amount of dryland agriculture went up from 9.88% to 18.54%. There were small rises in plantation and water body. On the other hand, the amount of forest shrank by 12.13%, and the area that was called "other" shrank by 2.8%.

Gain and Losses Land Use in Kedungsepur

Table 5 shows changes in land use from 2012 to 2022. The table shows that all types of land use in Kedungsepur have undergone changes. Forests experienced the largest loss of land, namely 64,739.09 ha. Most of this land (73.62%) was used for dryland agriculture, followed by built-up land (15.47%), plantations (6.42%), and other uses (4.49%). The area of built-up land increased by 35,017.64 ha, with 33.93% of this increase coming from dryland agriculture, 28.81% from forests, 26.44% from rice fields, and 10.82% from other types of land.

Table 5. Gains and losses matrix of LULC in the Kedungsepur Area for 2012 and 2022. This matrix illustrates the distribution of land cover changes, indicating gains and losses in each class resulting from coversions among land use/land cover types.

Land use class	Area 2012 (ha)	Change in 2022 (ha)						
		Ba	Ht	Lt	Ln	Pk	Pt	Sw
Ba	16,358.23	0.00	–496.30	–715.29	89.31	–9.91	294.64	3,233.29
Ht	164,100.07	496.30	0.00	–10,090.16	–508.83	–4,189.64	–48,026.19	–2,420.58
Lt	83,911.50	715.29	10,090.16	0.00	1,986.10	1,084.00	11,882.12	9,259.99
Ln	17,080.96	–89.31	508.83	–1,986.10	0.00	–70.50	–9,079.21	–4,206.63
Pk	11,741.79	9.91	4,189.64	–1,084.00	70.50	0.00	40.17	512.73
Pt	52,772.03	–294.64	48,026.19	–11,882.12	9,079.21	–40.17	0.00	1,336.52
Sw	188,113.12	–3,233.29	2,420.58	–9,259.99	4,206.63	–512.73	–1,336.52	0.00

Description: Ba: water body; Ht: forest; Lt: built-up land; Ln: others (scrub, open land, clouds, savannah, mining); Pk: plantation; Pt: agriculture; Sw: rice field.

Rice fields decreased by 7,715.31 hectares, with 69.41% of this area becoming built-up land and 10.02% becoming dryland agriculture. Plantations increased by 3,738.95 hectares, mostly due to forest clearing (86.89% of the total area). There was a small increase in water bodies (+2,395.74 ha), mostly due to rice fields being converted into water bodies (74.07%). The "Other" category decreased significantly (–14,922.92 ha), and most of the lost land was converted to dryland agriculture (60.84%) and rice fields (28.19%). The distribution and changes in land cover are shown in Figure 3.

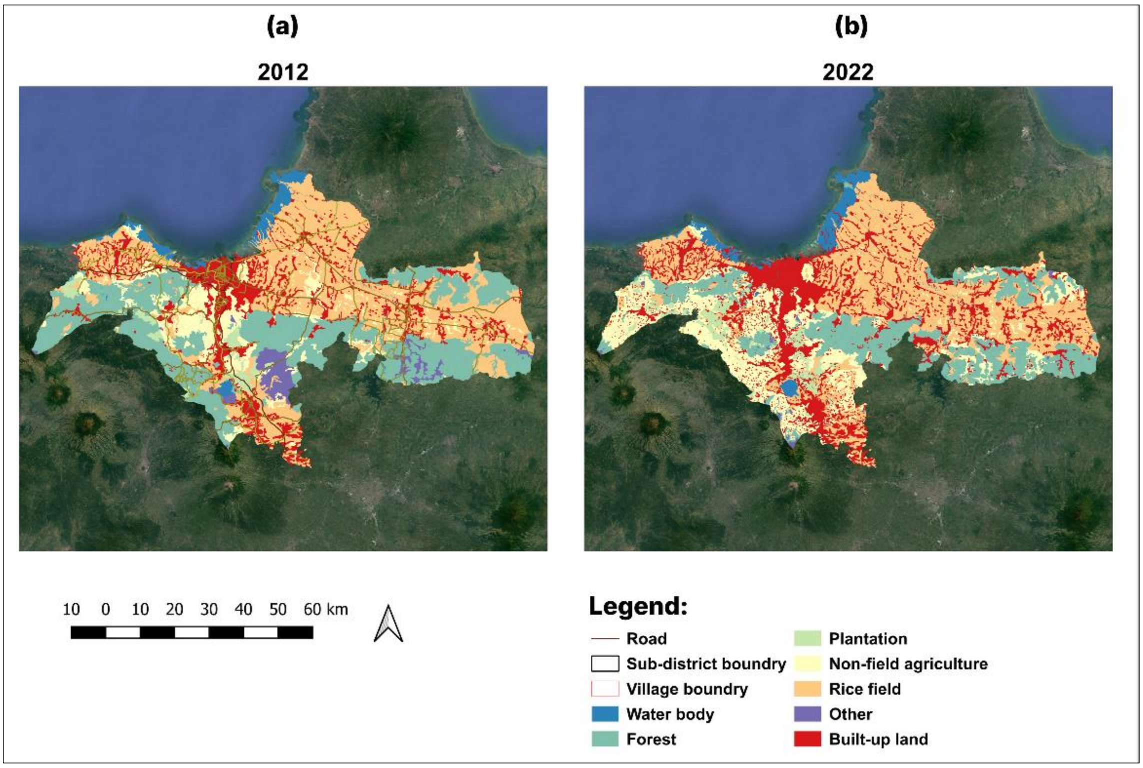

Figure 3. LULC in the Kedungsepur for 2012 (a) and 2022 (b). This figure presents the spatial distribution of land use and land cover classes for two time point and highlights the pattterns of land cover changes during the study period.

Rural-Urban Transformation

The RUI ranges from 0 to 1. It says that places with RUI values around 0 are "rural" and places with RUI values near 1 are "urban". The RUI analysis in Kedungsepur found that the number of places having urban characteristics went up from 235 in 2012 to 302 in 2022 (Figure 4). In the last ten years, 67 locations have changed from rural to urban. Kendal had the highest transformation rate, with 31% of the total transformed units in Kedungsepur. On the other hand, Salatiga and Grobogan had the lowest change from rural to urban, with only 6%. Demak, Ungaran (Semarang Regency), and Semarang, on the other hand, saw rises of 16%, 22%, and 18%, respectively.

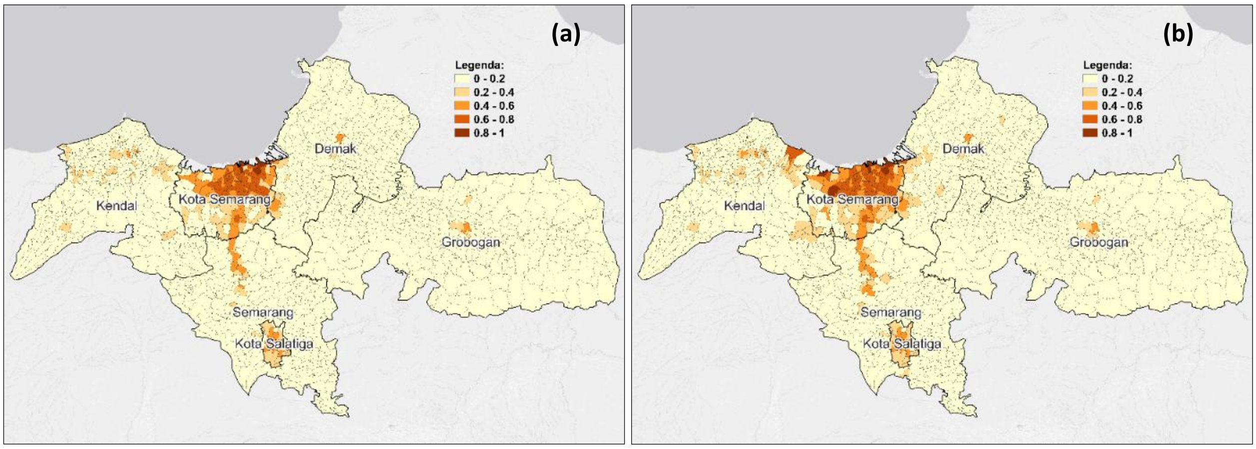

Figure 4. RUI in Kedungsepur for 2012 (a) and 2022 (b). This figure displays RUI values for each village-level unit, indicating rural characteristics (value closet to 0) and urban characteristics (value closer to 1), along with their spatial distribution across the metropolitan.

Moran's study gave a value of 0.83, which means that the data is clustered. This positive value (greater than zero) means that village units with high or low RUI values tend to group together [23]. We used a LISA analysis to get a better picture of the local spatial autocorrelation. The findings are given in Figure 5. This LISA analysis shows some intriguing changes over the past ten years. Figure 5 shows how the colours change to show how related different areas are. The white areas show that there is no spatial autocorrelation. At the same time, the other colours show varying levels of autocorrelation: red for high-high patterns, blue for low-low, light blue for low-high, and pink for high-low (Figure 5).

Figure 4 shows that there were big changes in the data from 2012 to 2022. The number of areas without spatial autocorrelation was down from 586 to 557, while the number of areas with spatial autocorrelation went up from 664 to 693. This change shows that there are more geographical links between regions over time. This could mean that development patterns have changed or that interactions between regions in the Kedungsepur metropolitan area have become more intense.

Spatial autocorrelation occurs when the value of a variable in one place is connected to the value of the same variable in places nearby. Areas that don't show spatial autocorrelation at first may start to show it when land use patterns alter, like when cities or industries grow, making patterns more organised. More people and better infrastructure also make spatial patterns more homogeneous. This phenomenon shows how important it is to know what causes these kinds of shifts in order to prepare better for the future [24].

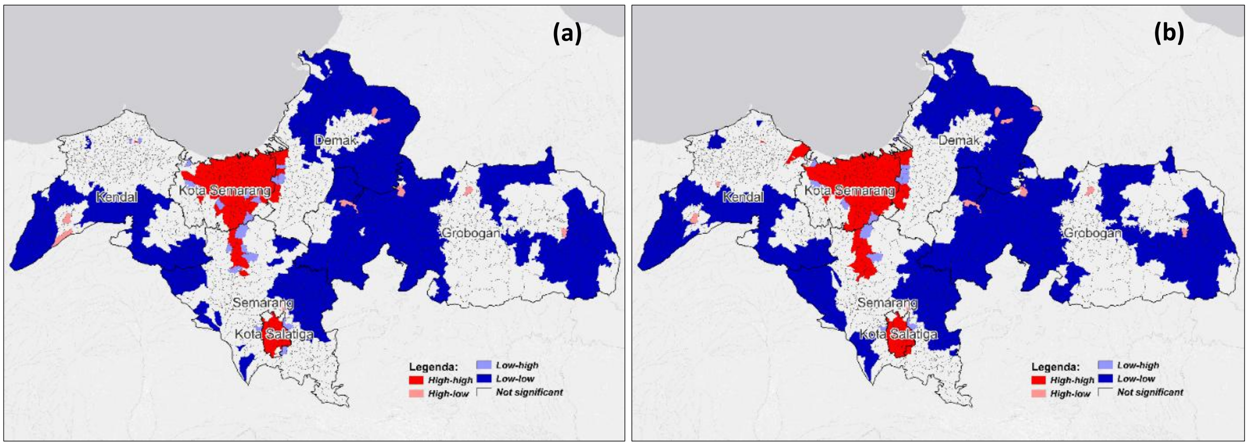

Figure 5. LISA's spatial cluster of RUI in Kedungsepur for 2012 (a) and 2022 (b). This figure shows the spatial autocorrelation patterns of RUI value across the study area, ilustrating urban clusters, rural clusters, and transitional peri-urban zones.

Figure 5 illustrates that the number of regions in the HH quadrant grew from 183 in 2012 to 202 in 2022. This quadrant has high RUI values and is surrounded by similar areas, which shows that development is happening in a concentrated way and that the economy is increasing. The HH quadrant's increase in the number of units shows that it could attract additional investment and make living better for people who live there [25]. In line with this, Balland et al. [26] says that the locations in this quadrant have a high concentration of productive activities, which can make up 40 to 80% of all economic activity in a metropolitan area. This means that the HH quadrant has a big impact on the economy of the metropolitan area.

The LL quadrant shows places with low RUI values that are bordered by other areas with low RUI values. This quadrant saw the number of regions grow from 452 in 2012 to 467 in 2022. This shows that the regions are more evenly spread out. Ding et al. [27] says that when economic, geographical, and cultural variables work together, they make a clearer pattern of uniformity. Even though these areas are considered rural, they don't have poor levels of welfare in absolute terms. On the contrary, they have the ability to do very well in social and environmental areas, even though they have problems with economic and institutional well-being [28,29]. So, it is necessary to make the right policies to make life better for the people who live in these places and make sure they play their part in helping the Kedungsepur Region grow as a whole.

In the Low-high (LH) quadrant, the number of units decreased from 19 in 2012 to 13 in 2022. This quadrant shows areas with high RUI values and places with low RUI values. The RUI value in this area has increased, which is why the number of units in this quadrant has decreased. Areas that were originally rural and bordered by cities will gradually become more urban. This process is not always related to more people moving to the area; it can also be related to changes or increases in the diversity of activities in the place itself. Randolph [30] refers to this as "urbanization from within", which means that urbanisation occurs without many people moving to the area, but rather through changes that occur in the place itself. The transition from rural to urban can also occur when the area effectively meets the requirements for urban designation. This is in line with Irwin et al. [31], which states that economic development that causes the rural landscape to mix with urban economic functions is what causes the formation of rural-urban spaces.

In 2012, the High-low (HL) quadrant had 10 area units. By 2022, it had 11 area units. This quadrant shows places with high RUI that are near places with low RUI. These places have the potential to spark growth and development. When established metropolitan areas and less developed rural areas work together, it can be easier to get to resources, technology, and job opportunities. This can enhance people's lives and boost the economy. This agrees with Yaqi [32], which says that the cluster makes a mutually advantageous link between urban and rural parts, which leads to synergies that make the region work better as a whole. Because of this, this process makes cities more appealing and also leads to more fair and long-lasting growth and development in the communities around them.

Discussion

Urbanization in the Kedungsepur metropolitan area has caused big changes in the environment and in the way people live, especially in peri-urban areas where built-up areas and dryland agriculture have grown at the expense of forests and rice fields. These changes have made the landscape less able to perform important ecosystem services, such as storing carbon, regulating water flow, and making soil fertile [33–35]. The loss of forest cover increases the likelihood of drought, erosion, and changes in microclimate [36,37]. The conversion of rice fields also makes it harder for water to stay in the ground and recharge groundwater, which makes urban water stress and flood risks worse, especially in lowland areas like Demak. These results show that urban expansion not only changes how land is used, but it also damages natural resources and makes the environment less resilient [38]. Other big cities, such as the Jakarta Metropolitan Area (*Jabodetabek*) and the Tokyo Metropolitan Area, have also seen similar tendencies. These cities have had environmental problems because of unregulated urban growth [39,40].

In this case, peri-urban agricultural land, which includes both dryland farming regions and rice fields, is an important ecological buffer that keeps the landscape permeable while also helping to grow food in the vicinity. However, converting these fields into built-up areas without proper zoning, coordinated irrigation management, and secure land tenure might put food security, hydrological stability, and biodiversity conservation at risk. The growth of dryland agriculture helps people adjust to market changes and serves as a transition zone in the process of urbanization. However, a lack of legislative focus on these transitional zones often leads to informal development and poor environmental regulation [41]. Similar occurrences have been recorded in the Chandigarh Metropolitan Area (India), where peri-urban wetlands serving as conservation zones have been transformed into residential zones [42], and in the Mexico City Metropolitan Area, where urban expansion has intruded upon designated preservation areas [43].

The RUI shows that urban growth in Indonesia, particularly Kedungsepur, is still mostly happening in a few key locations, as seen by the clustered RUI patterns. This concentration means that urban cores are putting more strain on the environment, which is causing land to degrade, air and water quality to get worse, and flooding and water shortages to become more likely. LISA analysis, on the other hand, shows that urban cores (high-high/HH) and rural areas (low-low/LL) are still separated by space, and that there are transitional zones with minimal spatial autocorrelation (LH and HL). These patterns show that there are weak connections between rural and urban areas, fragmented government, and poor coordination of the movement of products, services, and people [44,45].

Industrial agglomeration is a major driver of rural-urban transformation within this metropolitan framework. It speeds up land-use change, economic diversification, and mobility [46,47]. Industrial agglomeration creates business clusters and labor markets that boost productivity, wages, capital flows, and the growth of downstream sectors [48,49]. At the same time, it shapes new, multi nodal activity hubs, as seen in places like Solo Baru [50]. Industrial zones could be new growth centers on a provincial scale that help areas in the hinterland and lower differences between regions [51]. However, industrial agglomeration also puts strain on the environment by increasing emissions, water demand, and waste generation. This can be seen in the industrial areas of Semarang City, Semarang Regency, Kendal Regency, and Demak. On the other hand, places like Grobogan Regency that don't have strong economic forces change more slowly. This shows how important accessibility, industrialization, and government capacity are in determining metropolitan dynamics.

The results of LISA also show trends of suburbanization in Kedungsepur, such as the growth of cities into areas on the edges of cities, especially in the western and southern parts of Semarang City, and the conversion of farmland into homes and businesses (Figure 5). These suburban areas usually have little spatial autocorrelation, which means that there isn't much integration between rural and urban areas and that the flow of goods, services, and people is limited. Douglass's rural-urban connection theory says that targeted infrastructure investment, better functional connectivity, and coordinated service supply are all important for socio-economic integration. This trend fits with that theory [52,53]. The HH and LL quadrants don't work well together because of differences in demographics, socioeconomics, land use, and levels of urbanization. This makes landscapes look broken and makes it hard to monitor the environment [54].

Based on the above results, spatial planning policies need to set clear, geographically specific goals for increasing green cover, make sure that vegetated land is better protected, and strictly control urban sprawl in order to avoid the negative effects of the high rate of forest cover loss in the Kedungsepur metropolitan area. Additionally, green infrastructure and nature-based solutions should be included in spatial planning as important ways to improve ecosystem service capacity, especially for regulating water flow, preventing floods, and adapting to climate change [55,56]. These efforts need to be backed up by coordinated regional governance, effective incentive-based tools, and procedures for consistent monitoring and policy enforcement that work across administrative boundaries.

The identified pattern of suburbanization in the peri-urban areas of Kedungsepur indicates that planning and development processes to date have not been fully grounded in integrated peri-urban spatial management [57]. Accordingly, there is a need to strengthen multiscale planning approaches that link local, metropolitan, and regional policies, alongside the implementation of urban growth control instruments such as urban growth boundaries (UGB) to limit the expansion of built-up areas into ecologically valuable zones and productive agricultural land [58,59].

Furthermore, enhancing rural-urban connectivity as a foundation for sustainable metropolitan development can be achieved through the development of integrated physical and digital connectivity systems that facilitate labor mobility, goods distribution, and access to services [60]. Such connectivity should be complemented by the development of fair and mutually interdependent economic structures between urban and rural areas, the strengthening of inclusive cross jurisdictional governance, and the protection of rural ecosystem services including water provision, food production, and microclimate regulation that fundamentally support the sustainability of the urban core [61].

Conclusions

In the Kedungsepur Metropolitan Area, forest land has lost the most land cover, going down by 64,739.09 ha in the last ten years. On the other hand, built-up areas and dryland agriculture have grown by 35,017.64 ha and 46,224.99 ha, respectively. From 2012 to 2022, 67 locations changed from mostly rural to urban. This change happened in a very concentrated way, as shown by a Moran's I value of 0.83. Peri-urban areas in Kedungsepur are thus experiencing escalating pressures from industrial agglomeration and suburbanization, highlighting the necessity for spatially explicit green-cover objectives, stringent urban sprawl regulation via multiscale planning, and enhanced integrated rural-urban governance.

Author Contributions

APW: Writing-Review & Editing, Writing Original Draft, Visualization, Software, Methodology, Formal Analysis, Data Curation, Conceptualization; **AEP**: Validation, Supervision, Methodology, Conceptualization; and **DRP**: Validation & Supervision.

AI Writing Statement

During the preparation of this work, the authors used DeepL and Grammarly to ensure the proper English language structure and grammar. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the accuracy and integrity of the publication.

Conflicts of interest

There are no conflicts to declare.

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