The Presence of Rice Fields Amid Urban Expansion in a Medium-Sized City: A Case Study of the Surakarta Suburban Area

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Abstract: Urban expansion has become the most significant threat to rice fields, particularly in medium-sized cities. Surakarta is a medium-sized city experiencing rapid growth, surrounded by regencies that are also undergoing urban expansion. This study aims to investigate the presence of rice fields under the pressures of urban expansion dynamics over a 32-year multitemporal period covering 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2022. This research utilized remote sensing data processed through Geographic Information Systems (GIS). Supervised classification was applied to identify land cover over the 32-year period, including the extent of rice fields. The average annual urban expansion rate (AUER) and urban expansion intensity index (UEII) analyses were used to determine urban expansion's magnitude, speed, and direction. This study found that the most significant and fastest rate of urban expansion in Surakarta City occurred between 2020 and 2022. The results also showed that areas adjacent to the urban core (Surakarta City) experienced greater expansion speed than areas located farther away. Urban expansion pressure also resulted in a 40% loss of rice fields, with Klaten District experiencing the greatest loss. Maintaining rice fields in peri-urban areas can provide dual benefits by supplying rice for the city while preserving the local ecosystem. The dynamics of urban expansion in the Surakarta urban agglomeration, as revealed by this research, are essential for sustainable spatial planning in the region.

Keywords: medium-sized cities, remote sensing, rice fields, urban expansion, urban fringe

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1. Introduction

Today, urbanization has shifted towards small and medium-sized cities. A United Nations report [1] estimates that 68% of the world's population will live in cities by 2050, with small and medium-sized cities in Asia and Africa experiencing the fastest growth. Other studies have also confirmed that urbanization growth tends to be more pronounced in small and medium-sized cities compared to large cities [2, 3]. This situation can cause urban development problems if not properly planned. Urbanization often results in urban expansion, which is defined as an increase in built-up land [4]. Urban expansion that replaces natural vegetation has various impacts, such as the reduction of agricultural land [5–10], an increased carbon footprint, loss of biodiversity [11], increased surface temperature [12], decreased water quality [13], and ecosystem degradation [14]. Therefore, it is essential to examine the dynamics of urban expansion in small and medium-sized cities.

Urban expansion is understood as part of a complex and dynamic urbanization process controlled by biophysical and anthropogenic factors at different spatio-temporal scales [15]. Liu [4] also explained that urban expansion is the increase in urban built-up land resulting from the process of urbanization and urban land-use change due to human activities. Researchers have used various methods to investigate urban expansion. In the literature, remote sensing (RS) and geographic information system (GIS) techniques are commonly applied to effectively and efficiently investigate urban development dynamics. RS and GIS have been widely used to examine the patterns and dynamics of urban expansion in Hangzhou, China [16], Burayu, Ethiopia [17], and Alexandria, Egypt [18].

The loss of rice fields due to urban expansion has become the most serious threat, especially in the peripheral areas of small and medium-sized cities. Rice fields are a better choice for urban development because they are located on land with flat topography and are close to cities [19]. Rice fields play an important role in maintaining food security as well as functioning as green infrastructure, which is essential for sustainable urban development. Rice fields are a type of agricultural land that benefits food security, especially for rice crops, as rice has become the main food for Asian countries. In addition to food production, rice fields also provide valuable ecosystem services that support urban ecology, namely habitat provision for several species [20–22], landslide prevention [21], flood control [21, 23, 24], greenhouse gas emission control [25, 26], and pest (insect) reduction [27].

The loss of rice fields has become an important issue in Indonesia. To control the conversion of rice fields, the government has issued a policy to protect food agricultural land through Law No. 41/2009 on Sustainable Food Agricultural Land (LP2B). However, the conversion of agricultural land continues. The Ministry of Agrarian Affairs and Spatial Planning recorded a decline in rice fields of around 287,000 ha from 2013 to 2019, with Java Island accounting for 90% of this decline [28]. If this situation continues, it could threaten national rice production, as Java Island is the

granary of rice representing 52.24% of the national harvest area [29]. Agricultural land conversion is a logical consequence of urban growth, but protecting rice fields is necessary to help prevent a food crisis.

The Surakarta urban agglomeration (SUA) region is an urban agglomeration of regencies in Central Java Province, with Surakarta City as its core. In terms of city size, Surakarta City, with a population of 587,646 [30], is a medium-sized city with rapid growth and complexity [31]. The Surakarta urban agglomeration region, often called Subosukawonosraten, includes the city of Surakarta (Solo) as the core region with the surrounding regencies as suburban areas, namely Boyolali Regency, Sukoharjo Regency, Karanganyar Regency, Wonogiri Regency, Sragen Regency, and Klaten Regency. This region is located on a fertile plain between Mount Lawu and Mount Merapi and is drained by the Bengawan Solo River. Thus, it has vast rice fields as a regional food buffer (rice). Rice production reached 1.33 million tons per year, contributing 24.26% to Central Java's rice production or 4.22% of national rice production [29]. At the same time, Surakarta City experienced significant urbanization and had an impact on the increase in built-up land in the surrounding area [32]. As a result, rice fields located in the suburbs of Surakarta are threatened.

The dynamics of urban expansion and the loss of rice fields in the periphery of small and medium-sized cities on a multitemporal basis have received limited attention. Most studies were conducted in large metropolitan cities such as Beijing, China [33]; Guangzhou, China [4]; Accra, Ghana [34]; New Delhi, India [35]; Jakarta, Indonesia [36] and tended to explore land use/cover changes. Another study examined the impact of urban expansion on agricultural yields at two different points over 20 years but excluded corn, soybeans, and rice [5]. To fill this gap, this study aims to investigate the dynamics of urban expansion and rice field loss over a 32-year multitemporal period covering 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2022. This study can provide a deeper understanding of how the dynamics of urban expansion over time affect changes in rice fields. The results of this study are also significant for sustainable urban development.

2. Data and Methods

2.1. Study Area

The study area for this research was selected for its significant contribution to rice production and urbanization, as noted in the study background. Central Java Province, Indonesia, is divided into eight development priority regions, established based on the characteristics and potential of each city or regency. These eight development regions are Barlingmascakeb, Purwomanggung, Subosukawonosraten (SUA region), Banglor, Wanarakuti, Kedungsepur, Petanglong, and Bregasmalang [37]. Notably, of all the surrounding Central Java regions, the SUA region had a reduction in rice field area during the years 2003 to 2018 [38] as shown in Figure 1. The importance of studying the SUA region in this research is therefore evident.
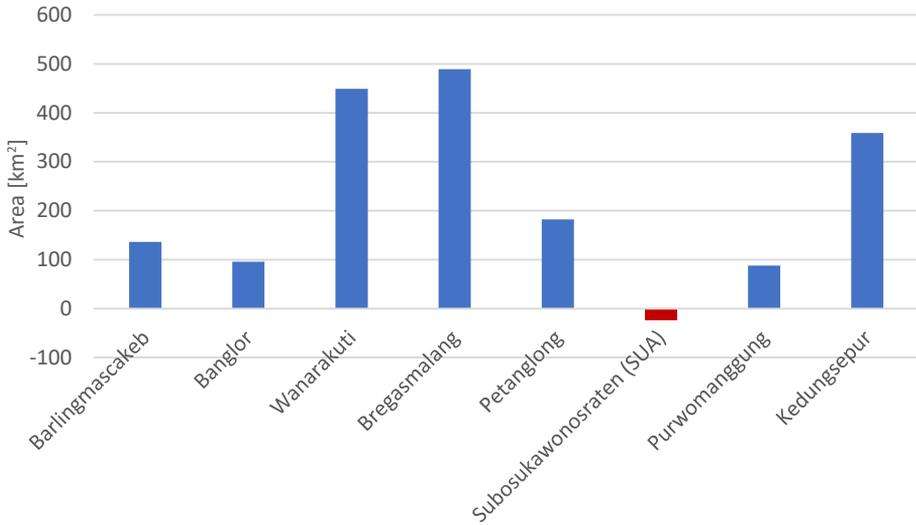
Fig. 1. Deviation in rice field area between 2003 and 2018
Source: own work based on data from [30]

The study area is the Surakarta urban agglomeration, a region in the Central Java Province of Indonesia that developed from a medium-sized city. It is situated geographically at 110°44′33.019″–110°54′1.456″ E and 7°50′56.795″–7°30′42.925″ S, with an area of 603,067 ha (Fig. 2).

This region lies in the upstream area of the Bengawan Solo watershed and is situated on a fertile plain between Mount Lawu and Mount Merapi, so it contains extensive rice fields. Rice production in this region is 1.33 million tons, contributing 24.26% of Central Java's rice production or 4.22% of national rice production [29]. On the other hand, this region is also experiencing significant urbanization.

2.2. Research Data

The suburban areas of Surakarta City referred to in this study are the administrative areas of the surrounding regencies, including Boyolali Regency, Sukoharjo Regency, Karanganyar Regency, Wonogiri Regency, Sragen Regency, and Klaten Regency. These regencies are small cities whose development is influenced by Surakarta City as a medium-sized city. This research employs spatial analysis methods using GIS and remote sensing to measure the dynamics of urban expansion. Land cover data for 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2022 were derived from 30-m resolution Landsat 4, 5, 7, and 8 imagery. The selected 32-year period (1990–2022) reflects the longest continuous timeframe with consistent and methodologically comparable satellite-based datasets. Analyzing this extended period is important for capturing long-term urban expansion trajectories, policy shifts, and structural land-use changes that unfold over multiple decades.
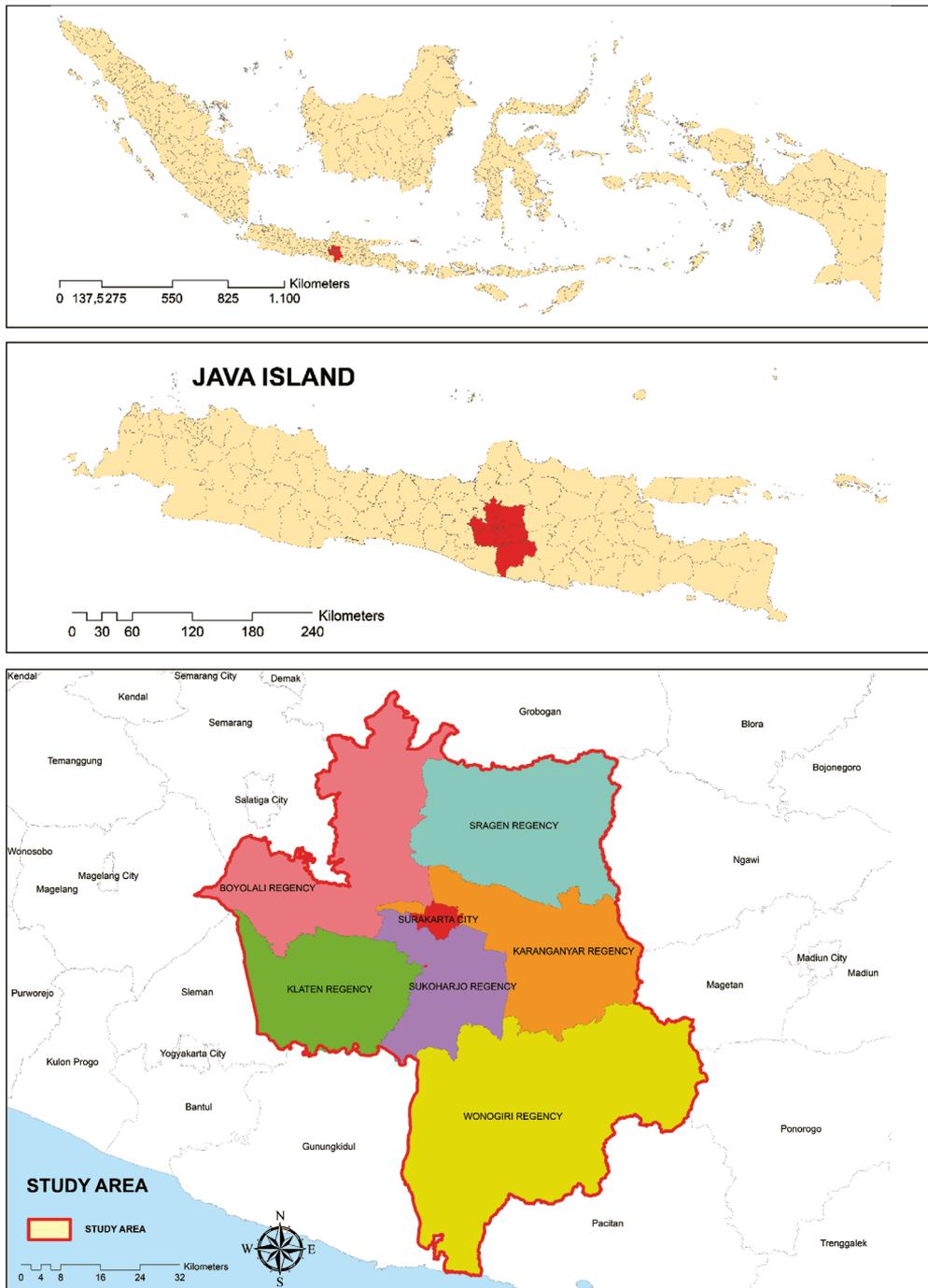
Fig. 2. Research study area

Shorter periods (e.g., 20 years) would not adequately represent these long-term transitions, while extending the analysis before 1990 was not feasible due to the limited availability of datasets. The dataset's temporal coverage extends to 2022, the most recent year with complete and verified data available when this research was conducted in 2023. This ensures consistency and reliability in the analysis across all data sources. The images were obtained from the U.S. Geological Survey (USGS) website (http://earthexplorer.usgs.gov/) through the Google Earth Engine platform. Google Earth Engine (GEE) has become a tool for analyzing and visualizing geospatial data, including remote sensing data [39]. Meanwhile, the regional administration map was obtained from the Geospatial Information Agency of Indonesia. Digital elevation model (DEM) data were also used to enhance spectral and topographic heterogeneity to facilitate classification. High-resolution imagery from Google Earth was used to validate the classification results. In addition, to assess the accuracy of the classification, some of the classified land uses were randomly selected for a field survey.

Table 1. Research variables and data

Research Objectives	Research Variables	Data	Data Source
Identifying multitemporal land cover years 1990–2022	Multitemporal land cover [3–7, 9, 10, 16, 17, 33–36]	Landsat 4, 5, 7, and 8 30-m resolution images; years 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2022	EarthExplorer (http://earthexplorer.usgs.gov/) using Google Earth Engine (GEE)
Analyzing the dynamics of urban expansion and loss of rice fields	Multitemporal rice field area [5–7, 9, 10, 14, 19]	Extent of land cover (settlement, forest, water, agriculture, rice fields, scrub, barren land)	Land cover analysis results
	Annual expansion rate [43]	Built-up area of the region every 5 years. Area of non-built-up area of the region every 5 years	
	Urban expansion intensity index [44]	Built-up area of each district at two different years. Total area per district	

2.3. Analysis

Land cover identification was conducted using Landsat images from 1990 to 2022 to analyze the temporal dynamics of land cover change as a result of Surakarta's urban expansion. Land cover was detected using GIS with the maximum likelihood supervised classification (MLC) method. Land cover classification used seven classes: water bodies, forest, bare land, settlements, agriculture, rice fields, and shrubs.

Accuracy assessment of the classification is needed to estimate how accurately pixels perform for each feature class [40]. This classification accuracy assessment can be addressed with Global Positioning System (GPS) techniques and Google Earth historical views. Based on the reference points of each classification year, two

accuracy assessment parameters were established, namely overall accuracy and the kappa coefficient [41]. The overall accuracy and kappa values of the land cover classification results in this study can be seen in Table 2. The statistical power of a kappa value of 0.81–1.00 is categorized as an almost perfect value [42]. Thus, the land cover classification results in this research can be used for further analysis.

Table 2. Validation and accuracy of classification results

Parameter	Image Year							
	1990	1995	2000	2005	2010	2015	2020	2022
Overall accuracy	0.88	0.90	0.91	0.95	0.93	0.93	0.94	0.94
Kappa	0.83	0.86	0.88	0.94	0.90	0.90	0.82	0.92

To measure the dynamics of urban expansion, the following measurement methods are used:
- Annual urban expansion rate (AUER)
  Measures the average annual land development rate between two time periods, the beginning of the study and the end of the study.

$$AUER_i = \left[\left(\frac{ULA_i^{t2}}{ULA_i^{t1}} \right)^{\frac{1}{t2-t1}} - 1 \right] \cdot 100 \qquad (1)$$

where $AUER_i$ is the annual urban expansion rate; ULA_i^{t2} and ULA_i^{t1} are the built-up land areas at time t_2 and t_1, respectively; and for this study, $t_1 = 1990$ and $t_2 = 2022$ [43].
- Urban expansion intensity index (UEII)
  UEII measures the growth of built-up areas, which illustrates the intensity of urban sprawl [44]. UEII is the annual average proportion of built-up area to total area. The UEII formula calculates the annual average growth area based on the total area:

$$UEII_{it} = \frac{ULA_{i,b} - ULA_{i,a}}{t} \Big/ TLA_i \cdot 100 \qquad (2)$$

where $UEII_{it}$ represents the annual average UEII in region i during time period t; $ULA_{i,a}$ and $ULA_{i,b}$ represent the built-up area in time periods a and b respectively in region i; and TLA_i represents the total area of region i. The UEII standard has an index value ranging between 0 and 1.92. The index is classified as follows: 0–0.28 indicates slow development; 0.28–0.59 indicates low speed; 0.59–1.05 indicates moderate speed; 1.05–1.92 indicates high speed; and values above 1.92 indicate very high-speed development.

To understand the relationship between the rate of rice field loss and the speed of urban expansion, a spatial overlay analysis was conducted involving UEII and rice field loss percentage classes in GIS. The results of the overlays were compared in order to understand the spatial and temporal relationship between urban expansion and rice field loss. The method framework can be seen in Figure 3.
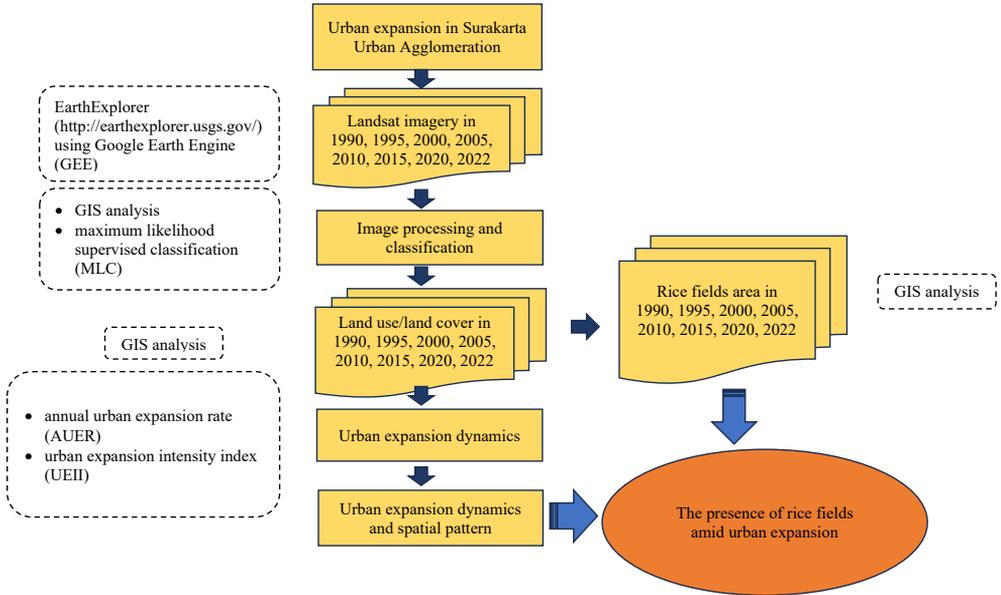

Fig. 3. Methodological framework

3. Results

3.1. Land Cover Identification in the Surakarta Agglomeration Region

Over 32 years (1990–2022), the Surakarta agglomeration region experienced significant land use changes. Figure 4 shows the spatial pattern of land use change from non-urban to urban in the Surakarta agglomeration region. In 1990, the agglomeration region of Surakarta did not develop massively; it developed only in the Surakarta area as the core city. However, it then continued to expand to the surrounding areas. The pattern of land use changed from non-urban to urban in areas adjacent to Surakarta and along main road corridors. Settlement land expansion also occurred in small towns relatively far from Surakarta City, such as in Sragen sub-district and Klaten sub-district. Based on Table 3 and Figure 5, from 1990 to 2022, settlement land expanded by 59,575 ha or 248%. Meanwhile, rice field land cover decreased by 83,325 ha or 40%.
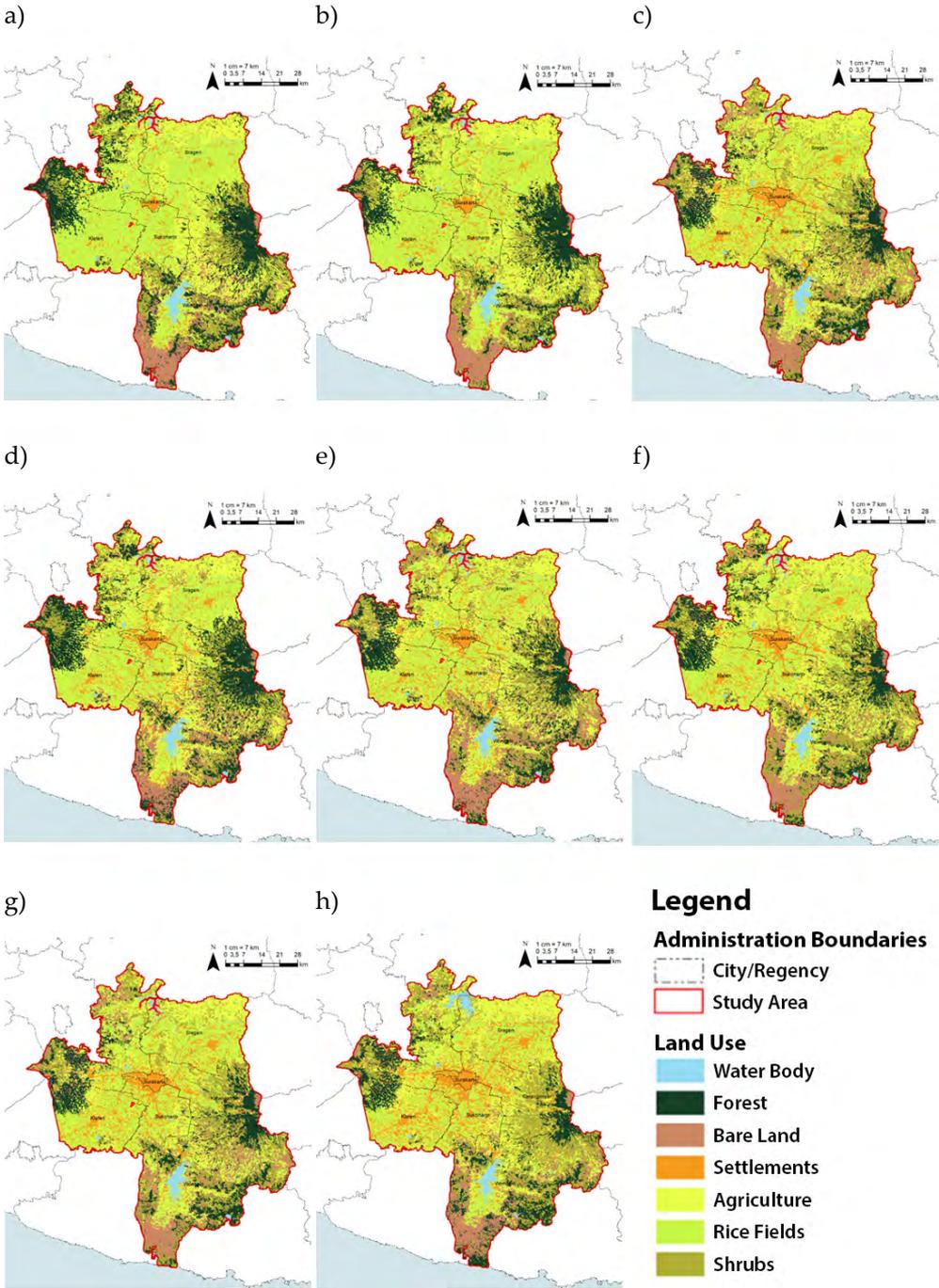
a)

b)

c)

d)

e)

f)

g)

h)

Legend

Administration Boundaries
- City/Regency
- Study Area

Land Use
- Water Body
- Forest
- Bare Land
- Settlements
- Agriculture
- Rice Fields
- Shrubs

Fig. 4. Surakarta urban agglomeration region land cover
in 1990 (a), 1995 (b), 2000 (c), 2005 (d), 2010 (e), 2015 (f), 2020 (g), and 2022 (h)

Table 3. Land cover in the Surakarta urban agglomeration region from 1990 to 2022

| Land Cover	Area [ha]							
	1990	1995	2000	2005	2010	2015	2020	2022
Settlements	24,035	31,680	41,624	48,187	52,672	53,213	59,919	83,610
Water body	10,211	10,690	12,252	9,904	10,770	10,879	9,977	11,544
Forest	107,827	91,584	71,214	110,731	80,453	80,465	77,609	71,733
Agriculture	117,117	115,870	140,379	125,785	120,352	134,181	116,047	123,831
Rice fields	208,692	208,001	155,242	151,434	146,518	145,053	147,472	125,367
Bare land	48,636	37,727	55,211	63,406	86,923	52,718	67,318	52,387
Shrubs	86,549	107,515	127,145	93,620	105,379	126,558	124,725	134,595
Total area	603,067	603,067	603,067	603,067	603,067	603,067	603,067	603,067
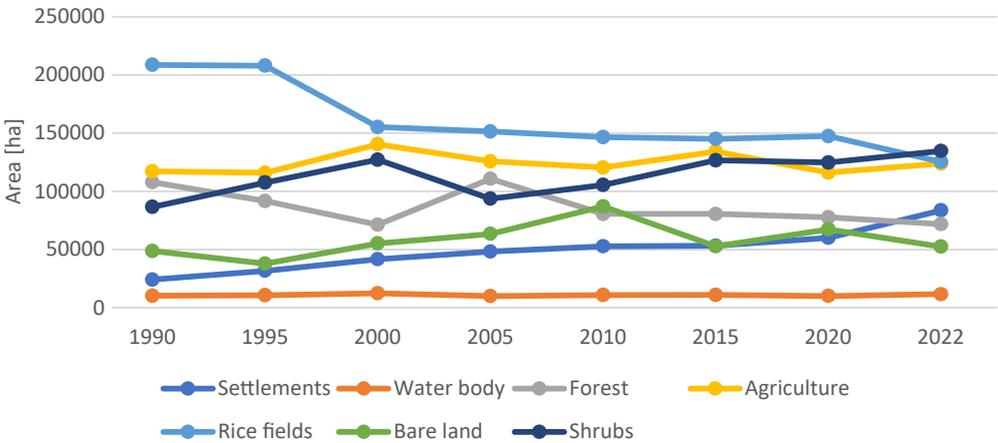
Fig. 5. Land cover change in the Surakarta urban agglomeration region from 1990 to 2022

3.2. Urban Expansion Dynamics

The spatio-temporal land cover data reveal the magnitude of year-to-year expansion in built-up and non-built-up areas. Based on land cover analysis from 1990 to 2022, the area of built-up and non-built-up land cover in the SUA is shown in Table 4. From that data, we can analyze the dynamics of urban expansion across the overall SUA region using the annual urban expansion rate (AUER). Based on the AUER calculation for every 5 years from 1990 to 2020, the most significant change occurred from 1995 to 2000. However, a much larger change is seen from 2020 to 2022, with an urban expansion rate of 18.12%, three times the greatest change over the past 32 years.

Table 4. AUER of Surakarta urban agglomeration every 5-year period

Year	Built-up area [ha]	Non-built-up area [ha]	AUER
1990	24,507	535,364	–
1995	31,706	571,728	5.29
2000	41,655	562,000	5.61
2005	48,224	555,431	2.97
2010	52,714	550,940	1.80
2015	53,256	550,398	0.20
2020	59,972	543,684	2.40
2022	83,680	519,975	18.12

Alongside AUER, the urban expansion intensity index (UEII) describes the speed of urban expansion in the Surakarta urban agglomeration region. Based on the UEII calculations shown in Table 5 and Figure 6, from 1990 to 2022, the urban expansion speed of the region as a whole was highest in the 2020–2022 period. In previous years, the SUA region consistently fell within the slow-to-low development speed classification. However, in 2020–2022, the UEII value reached 1.96, which is classified as a very high speed.

Table 5. UEII in Surakarta urban agglomeration region

City	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	2020–2022
Urban core							
Surakarta	4.71	1.79	1.25	−0.11	0.93	0.38	0.30
Suburban							
Boyolali	−0.03	0.17	0.10	0.40	−0.09	0.18	1.51
Karanganyar	0.39	0.30	0.35	−0.17	0.60	0.12	2.66
Klaten	0.67	0.46	0.32	0.58	−0.01	0.61	3.56
Sragen	0.18	0.36	−0.13	0.49	−0.05	0.41	2.54
Sukoharjo	0.84	1.11	0.77	−0.28	0.22	0.63	4.32
Wonogiri	−0.01	0.14	0.21	−0.07	−0.20	−0.06	0.54
Suburban average	0.52	0.42	0.35	0.49	0.41	0.39	2.52
Surakarta urban agglomeration	0.26	0.33	0.22	0.15	0.02	0.22	1.99

The highlighted cells represent the highest speed of urban expansion (based on UEII value) during each five-year period.
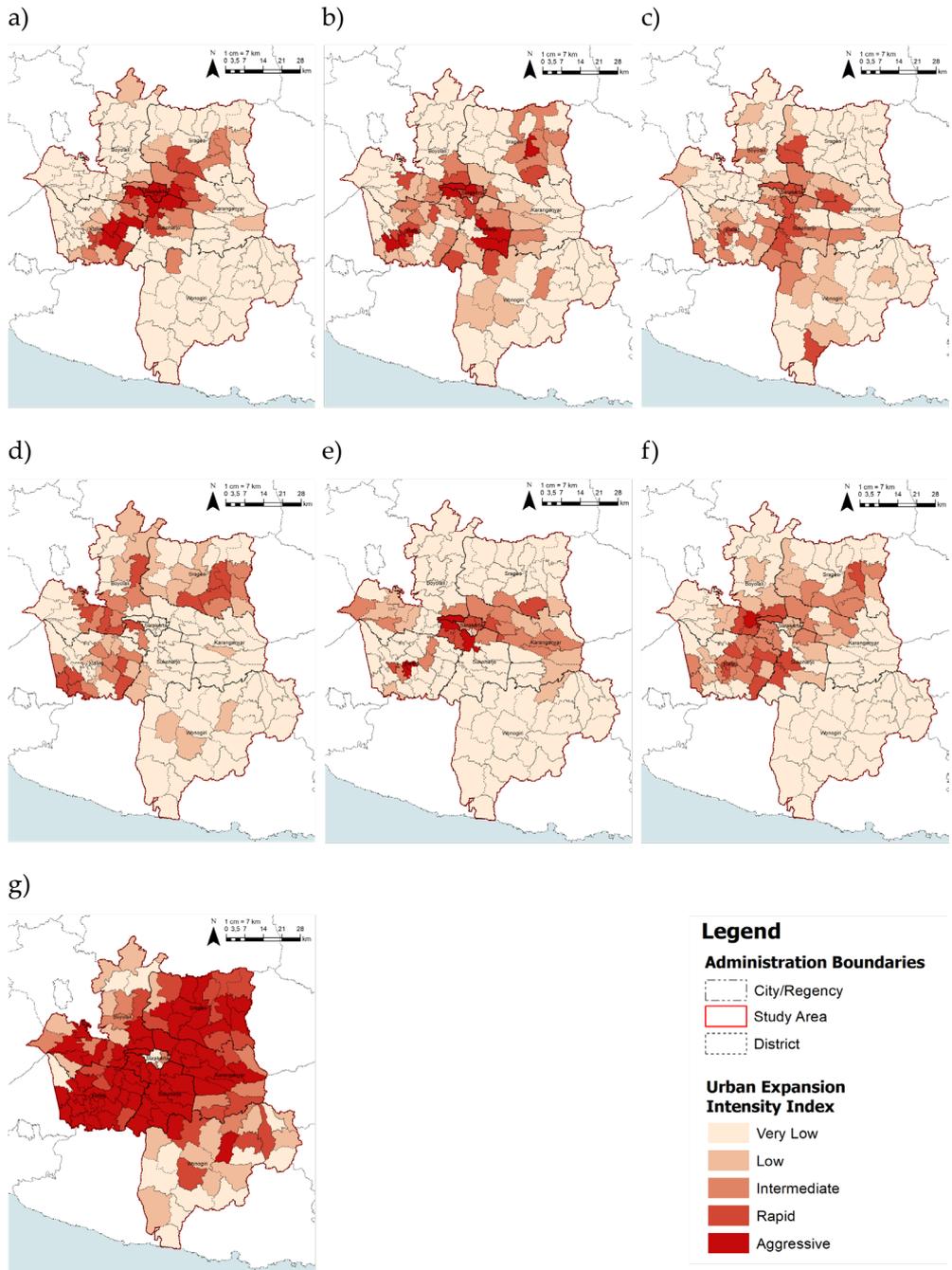
Fig. 6. Rate of urban expansion in the Surakarta urban agglomeration region over the period 1990–2022: a) 1990–1995; b) 1995–2000; c) 2000–2005; d) 2005–2010; e) 2010–2015; f) 2015–2020; g) 2020–2022

At the city/district level from 1990 to 2005, Surakarta had the highest urban expansion speed within the SUA region. However, in 2015 –2022, the highest speed of urban expansion was observed in Sukoharjo Regency. From 2020 to 2022, most districts/cities in the SUA region experienced very high rates of urban expansion.

Through this index, the direction of urban growth in each sub-district within each district/city in the Surakarta urban agglomeration can also be identified. From 1990 to 2005, the sub-districts in Surakarta City experienced a very high speed of urban expansion (aggressive). The opposite occurred in 2020–2022, when the sub-districts in Surakarta City no longer experienced high urban development, replaced by sub-districts in surrounding districts/cities.

3.3. Urban Expansion and Rice Field Losses

Rice fields in the SUA region decreased from year to year, although with fluctuations in the rate of change, as shown in Table 3. The overlay analysis of urban expansion speed and rice field loss (Fig. 7) illustrates that areas experiencing aggressive urban expansion also experience significant percentage losses of rice fields.
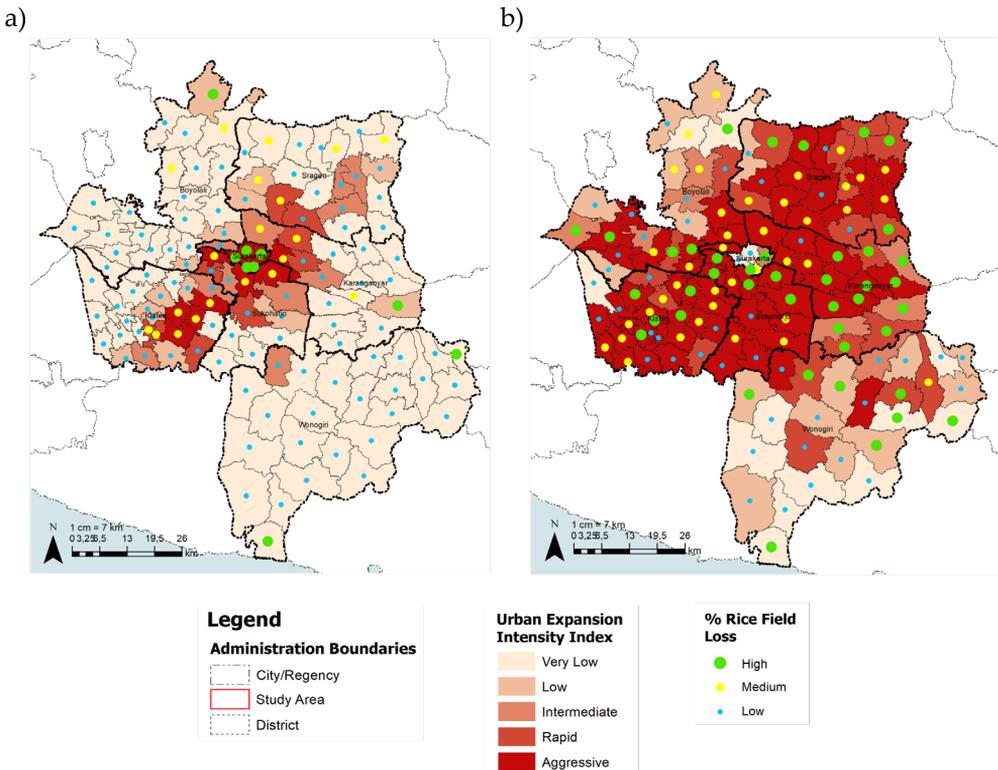

Fig. 7. Rate of urban expansion and rice field loss in the first year of 1990–1995 (a) and the last year of 2020–2022 (b)

In the first research period, between 1990 and 1995, Surakarta, which underwent aggressive urban expansion, experienced a high percentage of rice field loss. The same occurred in the most recent years, between 2020 and 2022, as districts with significant reductions in rice field areas also faced aggressive urban expansion. These results indicate that urban expansion is indeed a threat to the existence of rice fields, confirming that the pace of urban growth remains a key factor influencing the sustainability of rice fields.

Figure 8 shows that the change in the rice field area between 1990 and 2022 was dominated by conversion to residential land cover. Conversion of rice fields to settlements occurred across all SUA areas, with the largest in Surakarta City.
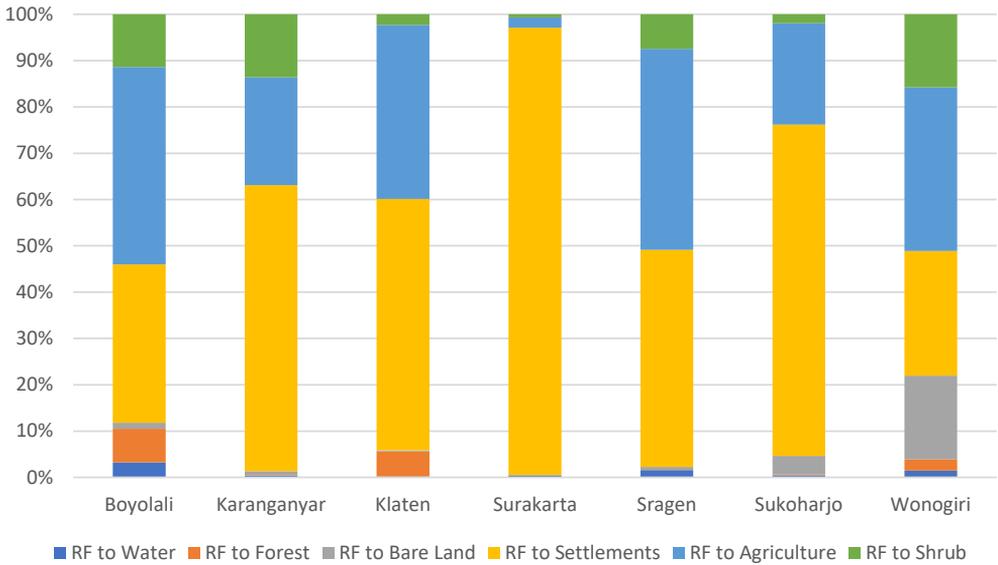

Fig. 8. Conversion of rice fields (RF) from 1990 to various other land covers by 2022

4. Discussion

The urban expansion dynamics in the Surakarta urban agglomeration can be viewed at both the regional scale and in terms of how the districts within the SUA region develop. Overall, the AUER and UEII values indicate that the SUA region was expanding very rapidly, especially from 2020 to 2022. Between 1990 and 2005, Surakarta experienced the fastest growth, after which expansion shifted to the outskirts of Surakarta from 2005 to 2022. This aligns with the development of metropolitan cities, where East and Southeast Asia experienced the highest infill growth from 1975 to 1990 and the highest edge expansion growth from 2015 to 2020 [45].

Based on the spatio-temporal land cover analysis, the most drastic loss of rice field area occurred between 1995 and 2000. However, the rice field area increased in the 2015–2020 period. This is due to the implementation of the Protection of Sustainable Food Agricultural Land policy in 2009 and the Control of Rice Field Conversion policy in 2019, both of which encouraged regional spatial planning efforts to maintain or restore rice fields within their jurisdictions. A similar policy is implemented in China as part of its food security strategy, where the central government enforces strict cropland protection measures [46, 47]. Agricultural land protection policies can help improve urban land use efficiency by restricting the transfer of agricultural land, maintaining the total area of agricultural land, and encouraging compact urban growth [48]. However, the situation in the SUA region following the implementation of the policy was slightly different. Although the policy was able to maintain the existence of rice fields, it could not sustainably control their conversion. The current rice field protection policy is ineffective at slowing urban expansion because the local government does not provide incentives for rice field owners to improve the welfare of rice field farmers. In addition, a rice field protection policy integrated with spatial planning policies, accompanied by the provision of incentives for rice field owners, is needed to limit urban growth and prevent the conversion of rice fields.

Most rice fields are converted into housing and settlements, while some are used for higher-value economic activities, such as shops and restaurants [49, 50]. The conversion of rice fields into built-up land is influenced by the population's need for housing and associated infrastructure. Unfortunately, most global urban settlements are primarily located in peri-urban cropland areas, leading to competition between urban expansion (built-up areas) and food production, conservation, and other ecosystem services [51, 52].

As the center of urban development, Surakarta City is expected to have a predominance of non-agrarian land cover. Consequently, Surakarta relies on the surrounding regencies to meet its food needs through rice cultivation. However, the districts located in Surakarta's surrounding regencies (the Surakarta urban fringe) are also affected by the expansion of built-up land from Surakarta. This trend threatens rice fields in the urban fringe districts, as they may be converted into built-up areas, including residential developments. The urban fringe serves, in fact, as an essential transition zone between urban expansion and the natural environment, providing ecosystem services (benefits people get from nature) that enhance the sustainability of the urban environment [53]. The sustainability of peri-urban cropland is crucial for improving sustainable development in urban and rural areas, especially considering the ongoing and inevitable process of urbanization [52].

Spatial and land-use planning policies can help preserve farmland and control urban expansion. For example, in Wuhan, China, two phases of land-use planning sought to control urban growth by placing restrictions on built-up areas and farmland. As part of the strategy, planners utilized land-use quota assignment, zoning

regulations, agricultural and land preservation, and administrative easing for land-use zoning. For every conversion from farmland to urban use, there was a corresponding offset through land consolidation and land reclamation [54]. The urban growth boundary (UGB) is also an example of a tool that is highly prevalent and popular among urban planners and local governments in developed countries to restrict rural-to-urban land-use conversion in a designated area and timeline. The UGB is designed to restrict urban expansion and protect agricultural land [55, 56]. As with other urban land-use planning practices, in Wuhan, the UGB divides the city into two zones: the developed side, which is inside the boundary, and the undeveloped side, which is outside the boundary and is allocated for preserving natural and protected areas [54]. Through policies to limit urban expansion, the existence of rice fields can be maintained, thereby ensuring that the food security of a region can also be maintained sustainably.

5.   Conclusion

Surakarta Urban Agglomeration region is experiencing urban expansion originating from Surakarta City. The dynamics of urban expansion from 1990 to 2022 can be seen based on the average annual urban expansion rate (AUER) and urban expansion intensity index (UEII) values. The AUER result shows that although the rate of urban expansion in the Surakarta urban agglomeration from 1990 to 2020 was decreasing, the expansion rate was increasing in the last two-year period (2020–2022). Based on the UEII results, the speed of urban expansion in the SUA region from year to year spatially moves from the sub-districts in Surakarta City to the sub-districts outside Surakarta City. The urban expansion shows a center-periphery pattern that starts from Surakarta City in the early 1990s and moves outside Surakarta City until the end of the study period (2022). The loss of rice fields is primarily associated with conversion into settlements to meet residents' housing and infrastructure needs, especially in the peri-urban areas. Additionally, rice fields are most vulnerable in regions experiencing aggressive urban expansion.

This study advances understanding of how spatio-temporal urban expansion affects the preservation of rice fields in a medium-sized city, a topic that has received limited attention in the literature. The findings may assist the Indonesian government in achieving long-term and medium-term development objectives on national self-reliance in sustainable food provision through the Food-Energy-Water (FEW) Nexus [57, 58]. Based on the targeted food security indicators, urban expansion must be managed and controlled. Uncontrolled urban growth threatens the preservation of rice fields, thereby jeopardizing the stability of national food resources and increasing the risk of food insecurity. Nonetheless, this research is limited by the availability of high-resolution satellite imagery data. Future research may improve spatio-temporal land cover analysis by using more advanced satellite imagery.

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CRediT Author Contribution

Z. M.: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review and editing, visualization, project administration.

I. B.: conceptualization, methodology, validation, supervision, writing – review and editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All of the research and analysis results that are included in the article have been published in the body of the article.

Use of Generative AI and AI-Assisted Technologies

Generative AI and AI-assisted technologies were used in this research to generate alternative texts for each figure and to check English grammar.

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