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Assessing Rice Food Availability Resilience Under Paddy Field Land Use Change in Sukabumi Regency

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Rice food availability resilience; Paddy field land-use change; Remote sensing; Agricultural intensification; Rice production.

ABSTRACT
Rice food availability is increasingly challenged by paddy field conversion driven by socioeconomic development and land-use transformation. However, reductions in paddy field extent do not necessarily indicate decreased food availability, as agricultural systems may respond through intensification and productivity improvement. This study evaluated rice food availability resilience under paddy field land-use change in Sukabumi Regency, West Java, Indonesia, during 2000–2020 by integrating Landsat-based spatial analysis with agricultural production indicators. Paddy field dynamics were analyzed using multi-temporal Landsat imagery through Object-Based Image Analysis (OBIA) and Random Forest classification. Agricultural responses were assessed using harvested area, cropping intensity, productivity, rice production, and the Production Efficiency Index (PEI).The results showed that paddy field area declined from 71,641.44 ha in 2000 to 65,982.15 ha in 2020, representing a 7.9% reduction, with the largest decline occurring in rainfed paddy fields. Despite this reduction, rice production increased from 622,189 tons to 931,328 tons, supported by increases in harvested area, cropping intensity, and productivity, particularly within irrigated paddy field systems. The PEI increased from 8.68 to 14.12 ton ha^{-1}, indicating improved production efficiency relative to available land resources. These findings indicated that rice food availability resilience in Sukabumi Regency was supported by agricultural adaptation strategies, particularly through intensification and productivity enhancement rather than land expansion.Nevertheless, productivity improvements may not indefinitely compensate for continued paddy field conversion due to ecological and biophysical limitations. Integrating remote sensing-based land-use change analysis with agricultural performance indicators provides a useful framework for evaluating food availability resilience and supporting sustainable paddy field management.

INTRODUCTION

Rice is a strategic agricultural commodity for sustaining food availability, particularly in developing countries where population growth, urban expansion, and socioeconomic changes continue to increase pressure on agricultural land. In Indonesia, rice remains the dominant staple food and a key component of national food security. Maintaining a stable rice supply has become increasingly challenging as productive agricultural land is converted into settlements, infrastructure, and other non-agricultural uses. The continued reduction of paddy fields raises concerns regarding the long-term capacity of agricultural systems to sustain production and support regional food security (Food and Agriculture Organization [FAO], 2023; Badan Pusat Statistik Republik Indonesia, 2021).

Agricultural land conversion represents a broader land-system transformation influenced by interactions among ecological processes, economic development, institutional arrangements, and human decision-making (Lambin & Meyfroidt, 2010; Meyfroidt et al., 2022). In rice-producing regions, reductions in cultivated area may decrease production capacity by limiting the land available for cultivation (Akliyah et al., 2022). However, the relationship between land loss and food availability is not always linear. Agricultural systems may respond through technological innovation, improved irrigation management, increased cropping intensity, and enhanced productivity, allowing production to be maintained despite increasing land constraints (Cassman & Grassini, 2020; Pretty et al., 2018).

In this context, resilience provides an important perspective for assessing whether agricultural systems can maintain their functions despite continuous pressure on land resources. Rather than focusing solely on the persistence of agricultural land, resilience emphasizes the capacity of farming systems to absorb disturbances, adapt to changing conditions, and continue performing essential functions over time (van der Lee et al., 2022; Ingram & Thornton, 2023). Within agricultural landscapes, rice food availability resilience reflects the capacity of production systems to maintain output despite declining land resources. This perspective is particularly relevant in densely populated regions where opportunities for agricultural expansion are increasingly limited and future production depends more on improving the performance of existing farmland than on developing new cultivated areas (Sundstrom et al., 2025).

Substantial paddy field conversion has been reported across Indonesia and is widely recognized as a challenge for sustainable agriculture. Previous studies have associated land conversion with declining agricultural capacity, increasing landscape fragmentation, and greater vulnerability of local food systems (Barchia et al., 2023; Firmansyah et al., 2021). Similar patterns have been observed in several regions where urban growth and economic transformation have accelerated agricultural land-use change (Siagian et al., 2019; Saputro et al., 2023). However, most previous studies have primarily focused on measuring the extent and spatial distribution of paddy field loss. Less attention has been given to whether agricultural production systems possess sufficient adaptive capacity to maintain food availability as cultivated land continues to decline.

Addressing this issue requires an assessment that connects agricultural landscape changes with actual production outcomes. Remote sensing has become an important tool for monitoring agricultural land because satellite observations enable consistent spatial assessments across large areas and extended periods. Advances in Object-Based Image Analysis (OBIA) and machine-learning algorithms, including Random Forest, have further improved agricultural landscape classification, particularly in areas with complex spatial characteristics (Blaschke, 2010; Belgiu & Drăguţ, 2016). Recent studies have also demonstrated the effectiveness of multispectral and synthetic aperture radar data for mapping rice fields, monitoring cultivation dynamics, and detecting agricultural changes at regional scales (Pham et al., 2020; Zhao et al., 2021; Kwak et al., 2021).

Nevertheless, spatial information alone cannot fully explain how land-use change affects food availability. Satellite imagery primarily represents physical landscape conditions at the time of image acquisition, whereas food availability is determined by broader production processes, including harvested area, cropping intensity, yield, and farm management practices. Agricultural statistics provide important information regarding these production indicators but offer limited insight into the spatial patterns and locations of land transformation. Therefore, integrating spatial observations with agricultural production statistics can provide a more comprehensive understanding of how farming systems respond to land-use change.

Differences between paddy field types also require consideration. Irrigated and rainfed systems differ in production potential, environmental sensitivity, and adaptive capacity. Irrigated paddy fields generally maintain more stable yields because water availability can be managed throughout the growing season. In contrast, rainfed systems depend more strongly on rainfall conditions and are therefore more vulnerable to climate variability and production uncertainty (IPCC, 2022; Jamal et al., 2023). Consequently, changes affecting these two production systems may have different implications for regional rice availability.

Sukabumi Regency, West Java, provides an appropriate case study for examining these relationships. The regency contains diverse landscapes, including irrigated and rainfed paddy fields, forests, settlements, and coastal ecosystems, while rice cultivation remains an important agricultural activity. At the same time, agricultural land in Sukabumi has experienced increasing pressure from land development and socioeconomic transformation. Previous studies have documented land-cover changes in Sukabumi and highlighted the importance of spatial analysis for understanding agricultural and ecosystem dynamics (Fitriani et al., 2024). Additional evidence from rainfed farming systems has also indicated increasing challenges related to climate variability and agricultural adaptation (Pramudia et al., 2024). These conditions raise an important question for agricultural planning in Sukabumi: whether the decline in paddy field extent has reduced regional rice availability or whether production systems have adapted to compensate for land loss.

This study addressed this research gap by integrating Landsat-derived spatial information with official agricultural statistics to evaluate rice food availability resilience under paddy field land-use change in Sukabumi Regency during 2000–2020. The analysis examined changes in irrigated and rainfed paddy field extent, harvested area, productivity, production performance, and production efficiency. Rather than interpreting paddy field conversion solely as evidence of declining agricultural capacity, this study evaluated whether improvements in agricultural management and production efficiency enabled remaining farming systems to compensate for land loss. Specifically, this study aimed to: (1) analyze temporal changes in irrigated and rainfed paddy field areas between 2000 and 2020 using Landsat-derived spatial information; (2) evaluate changes in harvested area, productivity, and rice production based on agricultural statistics; and (3) assess whether agricultural intensification and productivity improvements contributed to maintaining rice food availability resilience under declining paddy field extent.

Through this integrated approach, this study proposed a resilience-oriented assessment framework for evaluating food availability under changing agricultural landscapes. By combining remote sensing observations with production statistics, the study demonstrated that rice availability resilience depends not only on paddy field extent but also on the capacity of agricultural systems to utilize remaining land more efficiently. This perspective provides a broader foundation for understanding agricultural adaptation and supports more informed strategies for sustainable paddy field management in regions experiencing persistent land-use pressure.

METHOD

Research Design And Analytical Framework

This study employed an integrated spatial-statistical approach to evaluate rice food availability resilience under paddy field land-use change in Sukabumi Regency, West Java, Indonesia. The analytical framework was developed from a land system resilience perspective, emphasizing the capacity of agricultural systems to adapt to environmental and socioeconomic pressures (Lambin & Meyfroidt, 2021; Meyfroidt et al., 2022; van der Lee et al., 2022). In this study, resilience was assessed based on the capacity of rice production systems to maintain production functions despite reductions in paddy field availability.

The analysis was based on the assumption that changes in paddy field extent do not necessarily correspond directly with changes in food availability. Although agricultural land reduction may limit production capacity, farming systems may respond through adaptive strategies, including increased cropping intensity, productivity improvement, improved irrigation management, and more efficient utilization of existing land resources (Cassman & Grassini, 2020; Pretty et al., 2018). Therefore, rice food availability resilience was evaluated through the integrated assessment of three complementary components:

1. **Paddy field land resource dynamics**, representing changes in the spatial availability of agricultural land;
2. **Agricultural adaptation capacity**, represented by harvested area, cropping intensity, and productivity; and
3. **Rice production performance**, representing the ability of the agricultural system to maintain or increase production under declining land availability.

The analytical framework is summarized as follows:

Paddy field land-use change
↓
Change in agricultural land availability
↓
Agricultural adaptation response
↓
Cropping intensity and productivity improvement
↓
Rice production capacity
↓
Rice food availability resilience

The framework follows the principle that resilience is determined not only by the ability to withstand disturbance but also by the capacity of agricultural systems to adapt and sustain essential functions under changing conditions (Ingram & Thornton, 2023; Sundstrom et al., 2025).

Study Area

The study was conducted in Sukabumi Regency, West Java Province, Indonesia (Figure 1). As one of the largest administrative regions in West Java, Sukabumi encompasses diverse landscapes, including irrigated and rainfed agricultural areas, forests, settlements, mountainous terrain, and coastal ecosystems. Over recent decades, the regency has experienced substantial land system transformation associated with population growth, economic development, infrastructure expansion, and changing rural landscapes.

Rice cultivation remains a major agricultural activity in the region and is supported by both irrigated and rainfed paddy field systems. These production systems differ considerably in water availability, production stability, and sensitivity to environmental change. Irrigated paddy fields generally achieve higher and more stable yields because water supply can be regulated throughout the growing season. Rainfed systems, in contrast, depend largely on seasonal rainfall and are therefore more vulnerable to climate variability and production uncertainty (IPCC, 2022; Jamal et al., 2023).

Sukabumi Regency was selected for three reasons. First, it represents an agricultural landscape undergoing continuous pressure from land-use transformation. Second, the coexistence of irrigated and rainfed paddy fields provides an opportunity to compare the adaptive capacity of contrasting production systems under similar regional conditions. Third, previous studies have documented ongoing land-cover change and agricultural challenges in the regency, supporting its suitability for evaluating the relationship between land-use dynamics and rice food availability resilience (Fitriani et al., 2024; Pramudia et al., 2024).

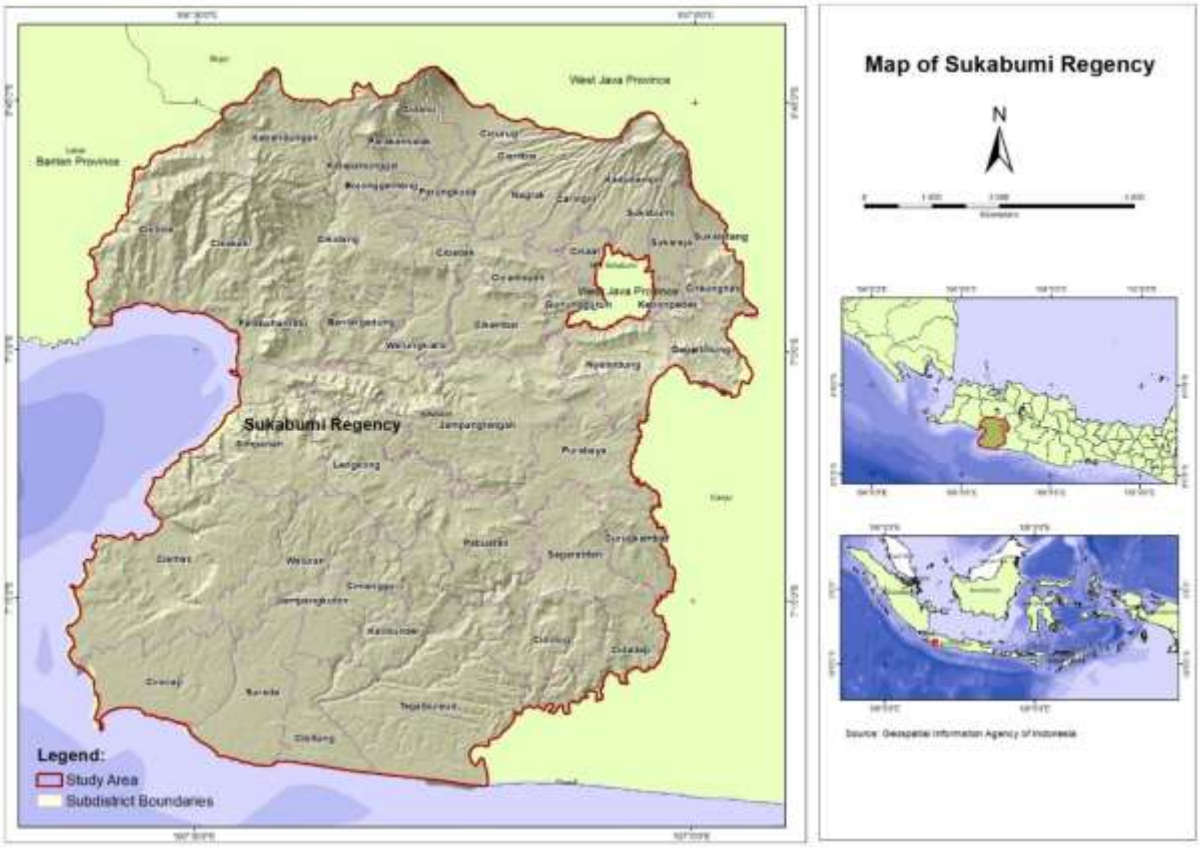

Figure 1. The Study Area Map of Sukabumi Regency

Data Sources

This study integrated two complementary datasets: Landsat-derived spatial information on paddy field distribution and official agricultural statistics. The spatial dataset was used to quantify land-use dynamics, whereas the statistical dataset was employed to evaluate changes in agricultural performance and rice production during the study period.

1. Landsat-Derived Paddy Field Spatial Dataset

Spatial information on paddy field distribution was obtained from Landsat-based land cover maps representing three observation years: 2000, 2010, and 2020. The dataset was produced through a previous study conducted under the broader research program entitled "*Modeling Land Use Planning Based on Rice Food, Water, and Carbon Ecosystem Services: A Case Study in Sukabumi Regency, Indonesia.*"

The original land-cover classification employed an Object-Based Image Analysis (OBIA) approach combined with the Random Forest machine-learning algorithm. By integrating spectral characteristics with the spatial attributes of image objects, this approach improves the identification of agricultural land, particularly within heterogeneous tropical landscapes (Blaschke, 2010; Belgiu & Drăguţ, 2016).

The resulting spatial database distinguished two paddy field categories: irrigated and rainfed systems. In the present study, the classified Landsat dataset was used directly without additional image processing or reclassification. The analysis focused on interpreting long-term spatial dynamics of paddy field land-use change and their implications for rice production resilience rather than reassessing classification performance

2. Agricultural Statistical Dataset

Agricultural production data were compiled from official publications of the Central Bureau of Statistics (BPS) of Sukabumi Regency together with national agricultural statistics. The dataset included paddy field area, harvested area, rice productivity, and total rice production. Data from 2000 to 2020 were selected to correspond with the Landsat observation years, enabling direct comparison between spatial land-use dynamics and agricultural production performance. The indicators used in this study are summarized in Table 1.

Table 1. Agricultural Indicators Used for Assessing Rice Food Availability Resilience

Indicator	Unit	Function
Paddy field area	ha	Represents agricultural land availability
Harvested area	ha	Represents cultivation intensity
Productivity	ton ha^{-1}	Represents production efficiency per cultivation area
Rice production	ton	Represents total food production capacity

All analyses were conducted separately for irrigated and rainfed paddy field systems before being synthesized at the regional level. This distinction was maintained because changes affecting each production system may influence rice food availability resilience in different ways.

Data Analysis

1. Paddy Field Land Use Change Analysis

Temporal changes in paddy field extent were assessed by comparing classified spatial datasets from the three observation periods (2000, 2010, and 2020). The magnitude of land-use change was calculated using the following equation:

$$LC = \frac{At - A0}{A0} \, x \, 100$$

where:
LC = percentage of land-use change (%)
$A0$ = initial paddy field area (ha)
At = final paddy field area (ha)

Negative values indicate a reduction in paddy field extent, whereas positive values represent expansion. The calculation was performed separately for irrigated and rainfed paddy fields to identify differences in land-use vulnerability between production systems.

In addition to evaluating net changes in paddy field area, a post-classification transition analysis was conducted by overlaying the 2000 and 2020 land-use maps. This approach was applied to identify the direction, magnitude, and spatial distribution of paddy field transitions over the study period. Unlike net area comparisons, which only describe overall gains or losses, transition analysis captures both persistence and reciprocal conversions within agricultural landscapes.

The overlay process generated six transition categories:

1. irrigated paddy field remaining irrigated paddy field;
2. irrigated paddy field converted to non-paddy land;
3. rainfed paddy field remaining rainfed paddy field;
4. rainfed paddy field converted to non-paddy land;
5. non-paddy land converted to irrigated paddy field; and
6. non-paddy land converted to rainfed paddy field.

These transition classes were subsequently visualized to examine their spatial distribution across Sukabumi Regency and to identify areas characterized by persistent cultivation, agricultural expansion, and conversion toward non-agricultural land uses. This approach provides a broader representation of agricultural landscape transformation because land systems are shaped not only by losses but also by persistence and reorganization processes (Lambin & Meyfroidt, 2010; Meyfroidt et al., 2022).

2. Harvested Area and Cropping Intensity Analysis

Changes in harvested area were analyzed to determine whether variations in rice production were associated with expansion of cultivated land or increased utilization of existing paddy fields. Since harvested area may exceed physical paddy field extent due to multiple cropping practices, cropping intensity was calculated as an indicator of land-use frequency:

$$CI = \frac{HA}{RFA} \, x \, 100$$

where:
CI = cropping intensity (%)
HA = harvested area (ha)
RFA = paddy field area (ha)

A higher cropping intensity value indicates that existing paddy fields were cultivated more frequently within a given year. Therefore, increases in cropping intensity were interpreted as evidence of agricultural intensification and adaptive responses to limited land availability. Through this mechanism, production systems can increase output without requiring proportional expansion of cultivated land (Cassman & Grassini, 2020; Pretty et al., 2018).

3. Productivity and Rice Production Analysis

Rice production dynamics were evaluated by examining the relationship between harvested area and yield performance. Total rice production was calculated using the following equation:

$$P = HA \, x \, Y$$

where:
P = rice production (ton);
HA = harvested area (ha);
Y = rice productivity (ton ha^{-1})

This equation was used to identify the relative contribution of three production drivers: (1) expansion or reduction of harvested area, (2) changes in cultivation frequency, and (3) productivity improvement. By separating these components, the analysis distinguished whether changes in rice production were primarily associated with land availability or improvements in agricultural performance.

Productivity trends were analyzed separately for irrigated and rainfed paddy fields to evaluate differences in production capacity between the two systems. This distinction was necessary because irrigation availability influences water control, cultivation stability, and yield performance. Therefore, variations in productivity between production systems provide an indication of their respective contributions to rice food availability resilience.

4. Production Efficiency Index (PEI)

To assess production capacity relative to available paddy field resources, the Production Efficiency Index (PEI) was calculated as an additional indicator:

$$PEI = \frac{P}{RFA}$$

where:
PEI = production efficiency index (ton ha^{-1} paddy field)
P = total rice production (ton)
RFA = total paddy field area (ha)

Unlike conventional production indicators that emphasize total output, PEI evaluates the amount of rice production generated per hectare of available paddy field. This indicator is particularly relevant for assessing agricultural resilience under conditions of declining land availability because it reflects how effectively remaining agricultural resources support food production. An increasing PEI value indicates that existing paddy fields generate higher production capacity despite reductions in total land extent. Therefore, PEI was used as a complementary measure to interpret whether agricultural systems maintained resilience through improved land-use efficiency rather than through expansion of cultivated area.

Integrated Interpretation of Rice Food Availability Resilience

The final assessment of rice food availability resilience was conducted by integrating spatial and agricultural indicators to evaluate how rice production capacity responded to changes in paddy field extent. The central question addressed in this framework was whether declining paddy field availability resulted in reduced production capacity or whether agricultural adaptation mechanisms enabled production systems to maintain their function.

Three resilience conditions were considered:

- **Condition 1: Land reduction and production decline.** This condition represents limited adaptive capacity, where reductions in agricultural land directly decrease rice production because the remaining production system cannot compensate for resource loss.
- **Condition 2: Land reduction and production stability.** This condition indicates moderate resilience, where improvements in management practices and land utilization maintain production performance despite declining paddy field availability.
- **Condition 3: Land reduction and production increase.** This condition reflects stronger adaptive capacity, where agricultural intensification and productivity improvement compensate for reduced land resources and allow production capacity to increase.

The interpretation framework follows resilience-based approaches in agricultural systems, which emphasize that sustainability depends not only on resource availability but also on the capacity of management systems to adapt, reorganize, and maintain essential functions under changing conditions (van der Lee et al., 2022; Ingram & Thornton, 2023).

Research Limitations

This study has several limitations that should be considered when interpreting the results. First, the spatial analysis was based on three representative observation periods (2000, 2010, and 2020). This temporal interval was sufficient to identify long-term land-use trends but did not capture annual fluctuations associated with climate variability, extreme weather events, or seasonal agricultural dynamics. Second, the assessment of rice food availability resilience focused primarily on production capacity. Other dimensions of food security, including accessibility, affordability, utilization, and stability, were not incorporated because they require additional socioeconomic datasets beyond the scope of this study. Third, the research examined agricultural system responses to land-use change rather than explicitly modeling the socioeconomic mechanisms driving paddy field conversion. Factors such as land prices, farmer decision-making, urban expansion pressure, and institutional influences were not quantitatively analyzed. Future studies could extend this framework by incorporating annual satellite observations, climate variability analysis, socioeconomic drivers of land conversion, ecosystem service assessments, and future land-use scenario modeling. Such integration would provide a more comprehensive understanding of agricultural resilience under increasing land-use pressure.

RESULT AND DISCUSSION

Spatial Dynamics of Paddy Field Land Use Change in Sukabumi Regency (2000–2020)

Landsat-derived land-use maps show a gradual decline in paddy field extent across Sukabumi Regency between 2000 and 2020. Total paddy field area decreased from 71,641.44 ha in 2000 to 65,982.15 ha in 2020, equivalent to a net loss of 5,659.29 ha or approximately 7.9% (Table 2). Changes in land cover are further illustrated through the visualization of paddy field class transitions (Figure 2) and the spatial distribution of transition classes (Figure 3). Taken together, these patterns point to sustained pressure on agricultural land resources associated with socioeconomic development and increasing competition for land.

Table 2. Temporal Changes of Paddy Field Area Based on Landsat-Derived Spatial Analysis

Year	Irrigated paddy field (ha)	Rainfed paddy field (ha)	Total paddy field (ha)
2000	16,476.39	55,165.05	71,641.44
2010	18,582.84	50,391.99	68,974.83
2020	15,905.79	50,076.36	65,982.15

The temporal patterns differed between irrigated and rainfed paddy fields. Rainfed areas declined continuously throughout the observation period, whereas irrigated paddy fields expanded between 2000 and 2010 before declining again by 2020. Such contrasting trajectories suggest that changes in the agricultural landscape were influenced not only by land conversion but also by shifts in irrigation availability, cultivation practices, and land management. Net changes in paddy field area therefore capture only part of the broader landscape transformation.

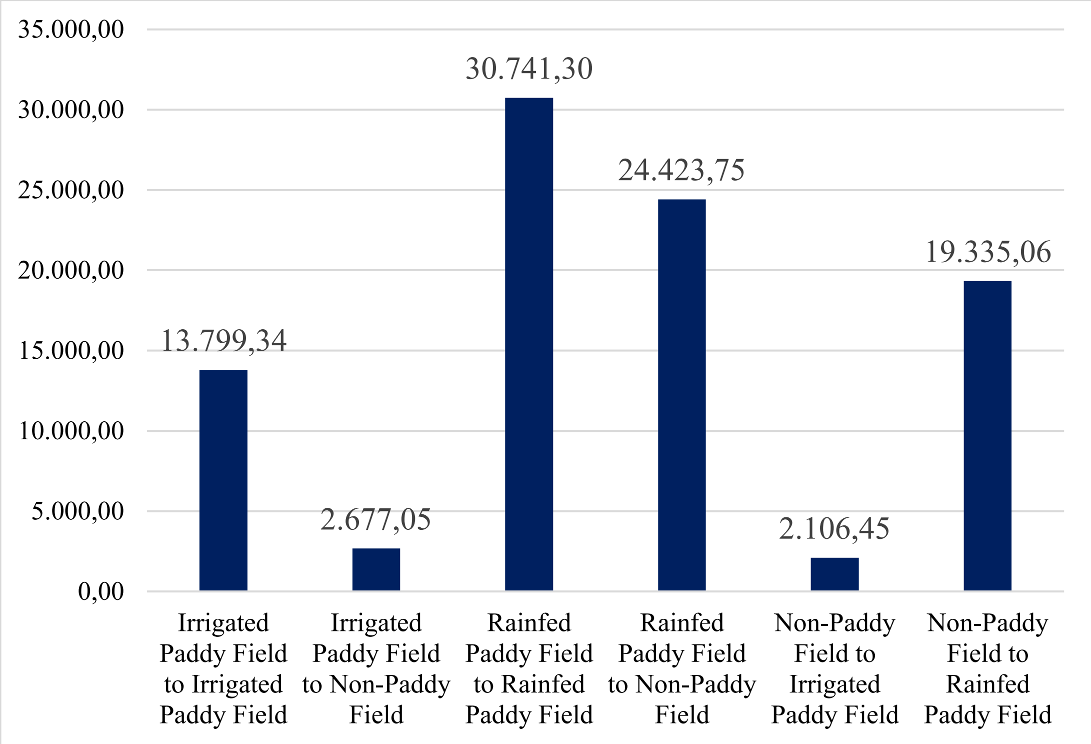

Figure 2. Visualization of Paddy Field Class Transitions in 2000–2020

The transition visualization clarifies how the overall decline in paddy field area occurred. During the study period, 13,799.34 ha of irrigated paddy fields and 30,741.30 ha of rainfed paddy fields remained unchanged, showing that a substantial proportion of the agricultural landscape retained its production function. At the same time, 2,677.05 ha of irrigated paddy fields and 24,423.75 ha of rainfed paddy fields were converted to non-paddy land uses, with conversion occurring more extensively in rainfed systems. New paddy fields also emerged from previously non-paddy areas, comprising 2,106.45 ha of irrigated paddy fields and 19,335.06 ha of rainfed paddy fields. These transitions occurred in both directions. Land persistence, conversion, and the establishment of new paddy fields took place simultaneously rather than as a single process of agricultural contraction. The observed net decline therefore reflects the cumulative outcome of opposing land transitions instead of a uniform reduction in paddy fields across the regency (Lambin & Meyfroidt, 2010; Meyfroidt et al., 2022).

The spatial distribution of transition classes was heterogeneous across Sukabumi Regency. Persistent paddy fields formed relatively continuous agricultural landscapes, whereas conversion to non-paddy land appeared as fragmented patches scattered across several parts of the regency. These differences are likely associated with variations in irrigation infrastructure, land suitability, accessibility, and local socioeconomic conditions, all of which influence land-use decisions. Irrigated paddy fields exhibited greater persistence throughout the study area, reflecting the role of irrigation infrastructure in sustaining rice cultivation. Rainfed systems followed a different trajectory. Their stronger dependence on seasonal rainfall made them more susceptible to climatic variability and environmental uncertainty, increasing the likelihood of conversion to non-paddy land (IPCC, 2022). Agricultural vulnerability was therefore not spatially uniform but varied according to local production conditions. Comparable patterns have been reported elsewhere in Indonesia, where agricultural land conversion is closely linked to socioeconomic development, urban expansion, and differences in agricultural productivity (Lambin & Meyfroidt, 2010; Siagian et al., 2019). Similar observations have also been documented in several agricultural regions, where paddy field conversion has emerged as a major challenge for maintaining long-term food security (Barchia et al., 2023; Saputro et al., 2023).

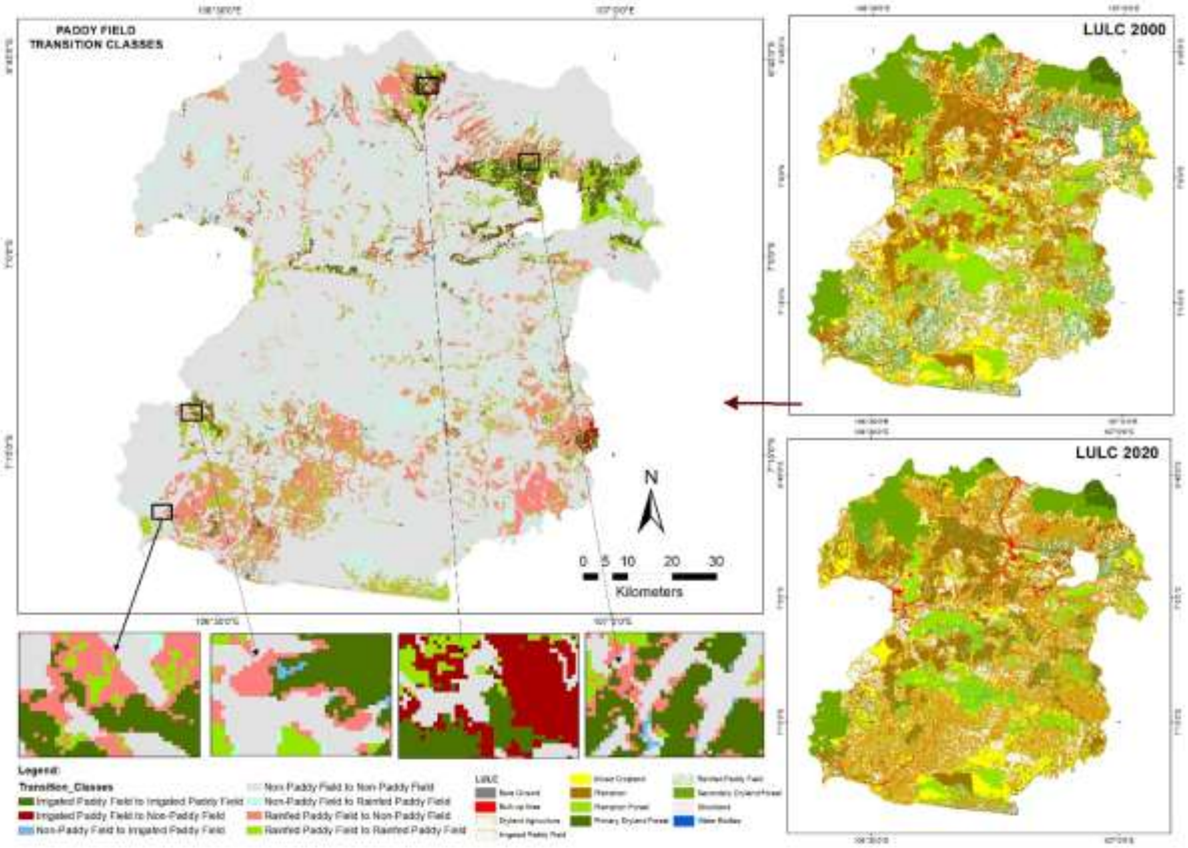

Figure 3. Spatial Distribution of Paddy Field Transition Classes in Sukabumi Regency During 2000–2020

The transition patterns presented in Table 2 and Figure 2 also show that changes in paddy field extent alone cannot fully explain the resilience of regional rice availability. Although the net loss of paddy fields reflects increasing pressure on agricultural land resources, extensive cultivated areas remained, while new paddy fields continued to develop in other locations. The agricultural landscape was therefore undergoing spatial reorganization rather than experiencing a simple and uniform decline. Land-use change, however, represents only one dimension of agricultural resilience. Food availability is also shaped by the ability of farming systems to respond to land constraints through improved management practices, higher cropping intensity, and productivity gains (Cassman & Grassini, 2020). For this reason, spatial land-use transitions need to be interpreted alongside agricultural production indicators to determine whether observed landscape changes ultimately weaken or sustain regional rice food availability resilience (Cassman & Grassini, 2020; Ingram & Thornton, 2023; Sundstrom et al., 2025).

Differences Between Landsat-derived Observation and Agricultural Statistics

Comparison between Landsat-derived paddy field mapping and official agricultural statistics revealed differences in the estimated extent of paddy fields (Table 3). The Landsat-based assessment showed a continuous decline in paddy field area from 71,641.44 ha in 2000 to 65,982.15 ha in 2020. In contrast, BPS agricultural statistics reported a relatively stable trend, with a slight increase in paddy field area during the same period.

Table 3. Comparison Between Landsat-derived and BPS-Reported Paddy Field Area

Year	Landsat-derived paddy field area (ha)	BPS paddy field area (ha)
2000	71,641.44	62,382.00
2010	68,974.83	64,077.00
2020	65,982.15	66,475.00

The differences between the two datasets reflect variations in data acquisition and measurement approaches rather than inconsistencies between sources. Landsat-based analysis identifies physical characteristics of agricultural landscapes through spectral responses, spatial patterns, and vegetation conditions captured at the time of satellite observation. Conversely, agricultural statistics are derived from administrative records and reporting mechanisms that describe agricultural activities within a specific management framework. Such differences are expected in dynamic agricultural landscapes. Paddy fields do not maintain identical physical characteristics throughout the year. Their spectral responses change according to cultivation stages, including land preparation, planting, vegetative growth, harvesting, and temporary fallow periods. As a result, satellite imagery captures the condition of paddy landscapes at a particular observation date, while agricultural statistics reflect cultivation activities accumulated over a broader reporting period (Blaschke, 2010; Zhao et al., 2021).

Previous research has demonstrated the potential of remote sensing for monitoring agricultural spatial changes, particularly when combined with object-based classification and machine learning techniques (Belgiu & Drăguţ, 2016; Pham et al., 2020). Nevertheless, spatial observations alone cannot fully describe agricultural functions, as production outcomes are also influenced by management practices, cropping frequency, and institutional definitions of agricultural land. The two datasets should consequently be viewed as complementary sources of information. Landsat-derived observations provide evidence of where paddy landscapes are changing, whereas agricultural statistics describe how agricultural production systems respond to those changes. Combining both approaches allows land-use dynamics and production performance to be assessed together, which is necessary for evaluating rice food availability resilience beyond a single perspective of either spatial change or statistical production trends.

Agricultural Intensification as an Adaptation Mechanism Under Paddy Field Reduction

Although the total extent of paddy fields declined during the study period, agricultural statistics showed a different pattern in harvested area development (Table 4). The increase in harvested area suggests that rice cultivation was maintained through more intensive use of existing agricultural land rather than through expansion of cultivated areas.

Table 4. Temporal Changes In Harvested Paddy Area

Year	Irrigated harvested area (ha)	Rainfed harvested area (ha)	Total harvested area (ha)
2000	114,285	30,387	144,672
2010	126,971	19,843	146,814
2020	141,814	31,208	173,022

Total harvested area increased from 144,672 ha in 2000 to 173,022 ha in 2020, representing an increase of approximately 19.6%. This increase occurred despite the reduction in paddy field extent, indicating that production growth was not primarily associated with agricultural land expansion. Instead, existing paddy fields were utilized more intensively to support higher production capacity. The relationship between available paddy field area and harvested area is further reflected by changes in cropping intensity (Table 5).

Table 5. Estimated Cropping Intensity Changes

Year	Paddy field area (ha)	Harvested area (ha)	Cropping intensity (%)
2000	62,382	144,672	232
2010	64,077	146,814	229
2020	66,475	173,022	260

Cropping intensity increased from approximately 232% in 2000 to 260% in 2020. The higher value indicates that paddy fields were cultivated more frequently, allowing production capacity to increase within limited land availability. Such adaptation is commonly observed in agricultural regions where expansion of cultivated land is constrained. Through sustainable intensification, agricultural systems can improve output by increasing resource-use efficiency rather than relying on continuous land conversion (Foley et al., 2011; Cassman & Grassini, 2020). A similar trend has been reported in Indonesia, where improvements in rice production have increasingly been associated with productivity enhancement and more intensive management practices rather than agricultural expansion (Gandharum et al., 2025). However, intensification cannot be considered a substitute for long-term paddy field protection. When applied beyond ecological limits, intensified cultivation may increase pressure on soil resources, water availability, and ecosystem functions (Pretty et al., 2018; Zhang et al., 2021). Maintaining productive agricultural land remains necessary to ensure that current adaptive capacity can be sustained in the future.

Productivity Improvement and the Strategic Role of Irrigated Paddy Fields

Changes in rice productivity provide further insight into how agricultural systems in Sukabumi Regency responded to land constraints during the study period (Table 6). While paddy field extent declined, production performance per unit area improved, indicating that remaining agricultural land contributed more efficiently to rice production.

Table 6. Changes in Rice Productivity

Year	Irrigated productivity (ton ha^{-1})	Rainfed productivity (ton ha^{-1})	Average productivity (ton ha^{-1})
2000	4.802	2.414	4.301
2010	6.254	3.777	5.919
2020	6.042	3.702	5.383

Average rice productivity increased from 4.301 ton ha^{-1} in 2000 to 5.383 ton ha^{-1} in 2020, representing an improvement of approximately 25.2%. The increase was largely associated with irrigated paddy fields, where productivity rose from 4.802 ton ha^{-1} to 6.042 ton ha^{-1} during the same period. Although productivity declined slightly between 2010 and 2020, irrigated systems consistently maintained higher yields than rainfed systems. The marked productivity gap between irrigated and rainfed paddy fields demonstrates the role of irrigation infrastructure in sustaining regional rice production. Reliable water availability allows irrigated fields to maintain more stable crop growth conditions and reduces exposure to rainfall variability. As a result, these areas contribute disproportionately to overall production capacity compared with lower-productivity rainfed systems.

The role of irrigation in improving rice productivity and strengthening adaptation capacity under environmental changes has also been reported in previous studies (Jamal et al., 2023; Hatta et al., 2023). Conversely, rainfed paddy fields remain more sensitive to climatic fluctuations because their production performance depends strongly on rainfall patterns and water availability (IPCC, 2022). These differences indicate that agricultural land protection should consider not only the extent of paddy fields but also their production function. The conversion of highly productive irrigated paddy fields may generate greater consequences for regional rice availability than the loss of areas with lower production potential. Maintaining irrigated agricultural systems is thus a key component in sustaining rice production resilience under continued land-use pressure.

Rice Production Resilience under Paddy Field Decline

The combined effects of increased harvested area and higher productivity were reflected in continuous growth in rice production throughout the study period (Table 7). Despite the reduction in paddy field extent, total rice production continued to increase, indicating that changes in land area alone did not determine production performance.

Table 7. Rice Production Changes

Year	Irrigated production (ton)	Rainfed production (ton)	Total production (ton)
2000	548,843	73,346	622,189
2010	794,102	74,947.01	869,049.01
2020	817,787	113,541	931,328

Total rice production increased from 622,189 tons in 2000 to 931,328 tons in 2020, representing an increase of approximately 49.7%. This trend indicates that production growth was sustained despite the gradual decline in paddy field area. Rather than relying on agricultural expansion, the production system showed patterns consistent with adaptation through higher cropping intensity, improved productivity, and more effective use of existing paddy fields. The Production Efficiency Index (PEI) provides additional evidence of this pattern (Table 8).

Table 8. Production Efficiency Index

Year	Production (ton)	Paddy field area (ha)	PEI (ton ha^{-1} rice field)
2000	622,189	71,641.44	8.68
2020	931,328	65,982.15	14.12

The PEI increased from 8.68 ton ha^{-1} in 2000 to 14.12 ton ha^{-1} in 2020, equivalent to an improvement of approximately 62.7%. Each hectare of remaining paddy field generated substantially greater production than at the beginning of the observation period. The increase in production was therefore achieved through gains in production efficiency rather than through expansion of cultivated land. Viewed from a resilience perspective, these results suggest that rice availability in Sukabumi Regency has been maintained by the capacity of agricultural systems to adapt to land constraints. Intensification, together with more efficient land utilization, enabled production to continue increasing even as the paddy field area declined. Similar conclusions have been reported in resilience studies, which show that system performance depends not only on resource availability but also on the ability to adjust management practices in response to changing conditions (van der Lee et al., 2022; Ingram & Thornton, 2023; Sundstrom et al., 2025). Even so, the observed increase in production efficiency should not be interpreted as evidence that continued paddy field conversion is without consequence. The benefits of intensification are bounded by ecological and biophysical constraints, including soil quality, water availability, and environmental sustainability. Once land conversion exceeds the adaptive capacity of agricultural systems, maintaining stable rice production will become progressively more difficult (Cassman & Grassini, 2020; Pretty et al., 2018; van der Lee et al., 2022).

Implications for Sustainable Paddy Field Management

The results indicate that sustainable paddy field management requires attention to both land conservation and production improvement. Increased rice production in Sukabumi Regency was achieved through intensification, higher productivity, and improved use of existing paddy fields. However, these mechanisms have limitations. Continuous paddy field conversion may reduce the capacity of agricultural systems to maintain food availability, particularly when productive irrigated areas are affected. Maintaining existing paddy fields, especially irrigated systems, should remain a priority in agricultural planning. These areas generally have more stable water availability and higher production capacity, making them important components of regional rice supply. In contrast, the conversion of rainfed paddy fields requires careful consideration because these systems are more vulnerable to productivity decline and land-use change.

Agricultural monitoring can be strengthened by integrating remote sensing analysis with agricultural statistics. Landsat-derived observations provide spatial information on the extent and location of paddy field changes, while statistical indicators explain how production systems respond to those changes. The combined use of both datasets allows land transformation and production dynamics to be evaluated simultaneously.

Future management strategies should promote sustainable intensification through improved cultivation practices, efficient irrigation management, and appropriate agricultural technologies (Cassman & Grassini, 2020; Pretty et al., 2018). Productivity improvement should not rely solely on increasing inputs but should also consider resource efficiency and environmental constraints. Furthermore, paddy landscapes should be recognized as multifunctional systems that support food production, rural livelihoods, ecosystem services, and environmental regulation. Balancing agricultural productivity with ecological functions is therefore necessary to maintain resilient paddy field systems under ongoing land-use change (UNEP, 2021; Meyfroidt et al., 2022).

CONCLUSION

This study examined rice food availability resilience under paddy field land-use change in Sukabumi Regency, West Java, Indonesia, by integrating Landsat-based spatial analysis with agricultural production indicators during the period 2000–2020. During the study period, the total paddy field area declined from 71,641.44 ha to 65,982.15 ha, representing an approximate reduction of 7.9%. Despite this decline, rice production continued to increase, indicating that changes in paddy field extent alone did not determine regional production capacity. Land conversion occurred predominantly in rainfed paddy fields, whereas irrigated paddy field systems remained relatively stable due to their higher productivity and more reliable water availability.

Production gains were supported by more intensive utilization of existing agricultural land. Harvested area increased from 144,672 ha in 2000 to 173,022 ha in 2020, while average rice productivity improved from 4.301 ton ha^{-1} to 5.383 ton ha^{-1}. Consequently, total rice production increased from 622,189 tons to 931,328 tons. The Production Efficiency Index (PEI) also increased from 8.68 to 14.12 ton ha^{-1}, reflecting improved production output relative to the available paddy field area.

These findings indicated that rice food availability resilience in Sukabumi Regency was supported by adaptation patterns involving agricultural intensification, productivity improvement, stronger performance of irrigated systems, and more efficient utilization of remaining paddy fields. However, improvements in production efficiency should not be considered a substitute for agricultural land protection. The adaptive capacity of farming systems remains constrained by soil conditions, water availability, and ecological limitations. Therefore, protecting productive paddy fields, particularly irrigated systems, remains essential for maintaining long-term rice availability. The integration of remote sensing-derived land-use information with agricultural production indicators provides a more comprehensive framework for assessing how landscape changes influence food availability resilience.

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STATEMENT OF CONTRIBUTION BY THE AUTHOR

Conceptualization: [Author 1];
Methodology: [Author 1];
Spatial data preparation: [Author 1];
Agricultural data analysis: [Author 1];
Formal analysis: [Author 1];
Visualization: [Author 1];
Writing – original draft preparation: [Author 1];
Writing – review and editing: [Author 2], [Author 3], [Author 4], [Author 5];
Supervision: [Author 2], [Author 3], [Author 4], [Author 5].
All authors have read and approved the final version of the manuscript.

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