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MORALITY BEFORE KNOWLEDGE

Analysis of agricultural land carrying capacity and projected food demand

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ABSTRACT

Background: Cilacap Regency is one of the leading rice-producing regions in Central Java and is widely recognized as a rice granary of the province. This study aims to assess the agricultural land carrying capacity and project future population growth in Cilacap Regency. **Method:** A quantitative descriptive approach was employed using secondary data sourced from the Cilacap Regency statistical reports for the years 2013–2023. **Findings:** The analysis reveals that the agricultural land carrying capacity in Cilacap consistently falls under Class 1 each year, indicating the region's strong ability to achieve rice self-sufficiency. However, population projections for 2033 show that certain districts—namely South Cilacap, Central Cilacap, and North Cilacap—may require an expansion of harvested area to meet future food demand. A key limitation of this study lies in the absence of projected agricultural land carrying capacity for the year 2033. **Conclusion:** Future research should address this gap to provide a more comprehensive outlook for sustainable food security planning in Cilacap Regency. **Novelty/ originality of this article:** The novelty of this study lies in assessing Cilacap Regency's agricultural land carrying capacity alongside future population projections, identifying potential food demand challenges, and informing sustainable rice self-sufficiency planning strategies.

KEYWORDS: agricultural land carrying capacity; future food demand; population projection; paddy field; food security.

1. Introduction

Environmental issues have increasingly become a pressing global concern, driven largely by the imbalance between land availability and the growing needs of living beings (Yudha & Kadir, 2021). Land, as one of the most vital and irreplaceable resources on Earth, holds a central role in supporting human welfare and maintaining the ecological balance of the biosphere (Pratama et al., 2021). It serves as the foundation for shelter, food production, industrial development, and ecosystem services, making it a critical natural asset that underpins the very survival of human societies. Within this broader landscape, agricultural land occupies a particularly significant position (Hedayati et al., 2022; Li et al., 2023; Mohapatra et al., 2022), since it is directly responsible for producing staple crops that sustain billions of people worldwide. Among these crops, rice occupies a unique and indispensable role, particularly in Asian countries such as Indonesia, where it not only functions as the staple food but also represents an economic and cultural cornerstone.

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Globally, rice serves as the staple food for over half of the world's population, illustrating its pivotal importance to food security at the international level. Approximately 90% of global rice is both produced and consumed within Asia, reflecting the region's overwhelming dominance in terms of supply and demand (Bandumula, 2018). Consequently, rice production in Asia does not merely serve domestic needs but carries broader implications for global stability and food supply chains. Ensuring stable rice production and distribution is therefore not only a matter of national policy but also of global concern. The growth trajectory of rice production has long been a subject of analysis, particularly given the persistent challenges faced by developing countries, where the food supply frequently struggles to keep pace with rapid population growth. Historical data reveal that rice production surged significantly between 2004–2013, fueled by the expansion of cultivated areas and large-scale investments in agricultural technology, irrigation infrastructure, and seed innovations (Bandumula, 2018). Nevertheless, the sustainability of this growth remains uncertain. For example, export growth decelerated to 4.01% between 2004–2012, largely as a consequence of the 2008 global rice crisis. During this crisis, many rice-importing countries shifted their strategies to prioritize domestic production in order to reduce dependency on volatile international markets (Bandumula, 2018). These dynamics clearly highlight the dual nature of rice: it is simultaneously a local staple and a globally traded commodity whose supply and demand are closely intertwined with international food security.

The importance of rice in Asia, and Indonesia in particular, cannot be overstated. For Indonesia, rice represents not only a primary food source but also a vital cultural symbol and an economic driver that shapes both rural livelihoods and national policy. Despite being among the largest rice producers in the world, Indonesia has paradoxically found itself in the position of being one of the largest importers during certain periods. This paradox underscores the fragile balance between domestic production and rising demand. The tension arises from two interrelated factors: the rapid growth of the population, which consistently increases food demand, and the declining availability of agricultural land, which constrains production potential. These structural pressures mean that even temporary disruptions in production can generate significant impacts on food availability, prices, and social stability. As population growth continues unabated, the urgency of managing rice production effectively becomes ever more critical. This tension is felt most acutely in regions that serve as the "rice barns" of Indonesia, areas whose agricultural productivity is essential for maintaining national food security.

Cilacap Regency in Central Java serves as a compelling case study of these dynamics. Geographically diverse and endowed with substantial natural resources, Cilacap possesses considerable potential for agricultural development (Nugroho et al., 2017). The region has historically been recognized as the "rice barn" of Central Java, consistently ranking as the province's largest rice producer and a critical contributor to both regional and national food supply. Several factors account for this role: fertile soils, favorable climatic conditions, and extensive irrigation systems that provide the foundation for intensive rice farming. Yet, this agricultural advantage is under increasing threat from demographic and spatial pressures. Rapid population growth has placed new demands on land resources, accelerating the conversion of farmland into residential areas, industrial estates, and infrastructure developments (Irsan & Fitrianingsih, 2023). Such land-use changes, if left unchecked, could reduce the available area for rice cultivation, undermining Cilacap's ability to maintain its role as a primary rice producer. In the long run, this trend risks not only diminishing Cilacap's status as Central Java's rice hub but also destabilizing food security across the region.

Against this backdrop, the concept of agricultural land carrying capacity emerges as a vital analytical framework. Carrying capacity refers to the capacity of a given area of land to sustainably support a certain population without degrading its resource base (Putri & Iswandi, 2023). In agricultural terms, it assesses whether the land can meet the food needs of its population, given its productivity levels and available resources. This concept is particularly relevant for rice production, as rice is both land- and water-intensive. A strong carrying capacity signifies that a region can achieve food self-sufficiency, ensuring that its population has consistent access to adequate food supplies. Conversely, when carrying capacity is exceeded, regions face risks of food insecurity, heightened dependency on imports, and greater vulnerability to global price fluctuations. Thus, carrying capacity is not merely an academic concept; it is a practical tool for policymakers and planners seeking to align population growth, land use, and food security objectives.

Understanding agricultural land carrying capacity in rice-producing regions such as Cilacap is therefore of critical importance. There are several reasons for this. First, rice farming remains the backbone of the local economy, providing employment for thousands of farmers and contributing significantly to the gross regional domestic product. Agricultural activities also sustain local communities by supporting traditional markets, supply chains, and related industries. Second, the maintenance of food security at the regional level directly affects national resilience. Given Indonesia's overwhelming reliance on rice as a staple food, disruptions in production at the local level can reverberate through the national food system. Third, the analysis of carrying capacity enables forward-looking planning by informing decisions about land allocation, urban development, and agricultural investment. By integrating population projections with assessments of agricultural productivity, policymakers can anticipate potential mismatches between food demand and supply, thus enabling proactive rather than reactive responses to future challenges.

While a number of studies have examined agricultural land carrying capacity in different settings (Dwirani et al., 2022; Rahmawati et al., 2023; Ratu et al., 2021; Kunu, 2020), specific research on Cilacap remains scarce. This is a surprising omission, given the regency's strategic role in Central Java's rice production system. Moreover, previous research has rarely incorporated long-term projections of food demand and land requirements specific to Cilacap. Such projections are essential for anticipating the consequences of continued population growth and land conversion. Without them, regional planning risks being reactive, addressing problems only after they arise rather than preventing them. Proactive strategies, informed by robust carrying capacity analyses, are necessary to safeguard both the agricultural base of Cilacap and the broader food security of Indonesia.

In addition, situating Cilacap within broader global challenges strengthens the case for such localized research. The sustainability of rice production worldwide is increasingly threatened by factors such as climate change, land degradation, and water scarcity. Climate variability can disrupt planting cycles, reduce yields, and increase vulnerability to pests and diseases. Land degradation, caused by soil erosion, nutrient depletion, and overuse of chemical inputs, reduces the long-term productivity of farmland. Water scarcity, exacerbated by competing demands from urban and industrial users, threatens the irrigation systems that rice production depends upon. These challenges are not abstract risks but tangible realities already affecting farmers in many regions. For Cilacap, these pressures intersect with population growth and land-use change, creating a complex nexus of threats that require careful management and forward-looking strategies.

From a broader perspective, these challenges are closely aligned with the objectives of the Sustainable Development Goals (SDGs). SDG 2 (Zero Hunger) directly addresses the eradication of hunger and the achievement of food security, both of which are tied to sustainable rice production. SDG 12 (Responsible Consumption and Production) emphasizes efficiency and sustainability in agricultural systems, including reducing post-harvest losses. SDG 13 (Climate Action) acknowledges the need to build resilience in agricultural sectors against climate variability. Finally, SDG 15 (Life on Land) underscores the importance of preserving ecosystems and preventing land degradation—objectives that resonate with Cilacap's challenge of protecting fertile rice fields from conversion. Thus, analyzing agricultural land carrying capacity in Cilacap contributes not only to national policy but also to global commitments under the SDGs.

Therefore, this study seeks to fill the research gap by analyzing changes in agricultural land carrying capacity and forecasting future land requirements in Cilacap Regency. By doing so, it aims to ensure that the regency can sustain its vital role as a key rice-producing region, even amid growing population pressures and competing land uses. The study also aspires to contribute to broader academic discourse on carrying capacity and food security by providing a detailed, localized case study that complements global and national perspectives. Ultimately, the findings will not only enrich scholarly understanding but also provide actionable insights for policymakers, local governments, farmers, and stakeholders. In so doing, the research will help safeguard Cilacap's role as the "rice barn" of Central Java and contribute to the resilience of Indonesia's broader food system in the face of twenty-first-century challenges.

2. Methods

This study employs a quantitative descriptive approach to analyze the agricultural land carrying capacity and project future land requirements for 2033 in Cilacap Regency, Central Java, Indonesia (Figure 1). The research focuses on evaluating whether current agricultural land can sustainably support rice production amid population growth and land-use changes.

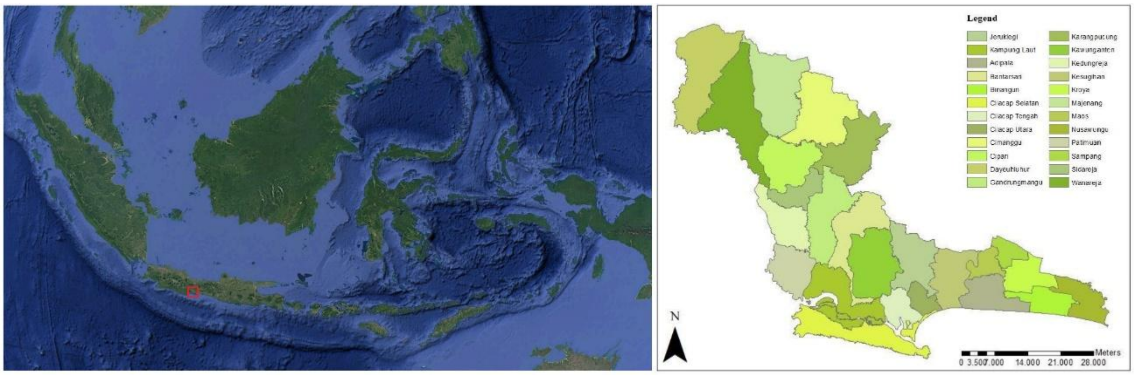

Fig. 1. Study location

2.1 Data collection and tools

Data were obtained from the Cilacap Regency Central Bureau of Statistics, covering harvested area, rice production, productivity, and population from 2013 to 2023. Additional references included agricultural and demographic studies to strengthen the analysis. Data processing utilized Microsoft Excel for statistical calculations and ArcMap 10.3 for spatial visualization.

2.2 Analytical framework

The agricultural land carrying capacity was calculated using an established formula integrating concepts from Odum, Christaller, and Ebener Howard. The index (φ) compares per capita harvested area (X) against the land required for food self-sufficiency (K). The Minimum Physical Requirement (KFM) was set at 0.1521 tons of rice/person/year, based on FAO and Indonesian nutritional standards. Productivity was derived by dividing total rice production by harvested area.

Results were classified into three tiers: high capacity ($\varphi > 2.47$), indicating sustainable food and livelihood support; optimal capacity ($1 < \varphi \leq 2.47$), meeting basic food needs but with limited surplus; and low capacity ($\varphi < 1$), failing to achieve self-sufficiency. The Optimal Population Size was then estimated by multiplying agricultural land carrying capacity by the current population, revealing the maximum population sustainable under existing land productivity.

2.3 Projection for 2033

Future land needs were projected using linear regression, accounting for population growth trends and historical productivity changes. This model assessed whether Cilacap's agricultural land can meet anticipated rice demand or requires expansion/intensification. The statistical data used for the projections were 2013 data, this was to standardize the initial data and projection targets such as several projection studies such as the study from Sidiq et al. (2024).

3. Results and Discussion

3.1 Agricultural land carrying capacity in Cilacap Regency

Cilacap Regency, comprising 24 districts, has demonstrated consistently strong agricultural land carrying capacity for both lowland and upland rice over the period 2013–2023. Agriculture plays a highly strategic role in the regional economy of Cilacap, functioning not only as a provider of food and raw materials for industry but also as a major source of employment and household income (Cilacap Agriculture Office, 2019). Beyond these functions, agriculture also underpins rural livelihoods and sustains the social fabric of local communities, making it an indispensable sector for both economic development and food security.

The agricultural sector makes a dominant contribution to the Gross Regional Domestic Product (GRDP). In 2016, agriculture accounted for 17.54% of the GRDP (excluding oil and gas), a proportion that remained relatively stable over time, with 17.53% recorded in 2014 and 17.78% in 2015. These figures reflect the structural stability of agriculture as a driver of economic output in Cilacap, even amidst demographic growth and land conversion pressures. Agriculture also continues to be the leading sector in terms of employment absorption, engaging 285,064 workers, the majority of whom (213,708 people) are employed in food crop production. Based on the 2013 Agricultural Census, Cilacap had 253,484 farming enterprises, predominantly managed by household units, indicating the persistence of smallholder farming systems that dominate Indonesia's agricultural landscape (Cilacap Agriculture Office, 2019).

This sector is supported by extensive land resources. The total agricultural area of Cilacap consists of 64,744 ha of paddy fields (30.27%), 60,084 ha of non-paddy agricultural land (28.10%), and 89,022 ha of non-agricultural land (41.63%). These land resources position Cilacap as one of the largest rice-producing regions and a critical buffer for food security in Central Java, contributing approximately 7% to the province's total rice production. In 2017, Cilacap produced 897,280 tons of rice, an increase compared to 888,960 tons in 2016, highlighting the regency's consistent productivity and resilience in meeting food demand.

In addition to irrigated and upland rice, secondary food crops such as maize, soybean, groundnut, mung bean, cassava, and sweet potato are also cultivated in the regency. However, due to limited planting intensity, production volumes of these crops tend to fluctuate annually. The agricultural sector in Cilacap further extends to horticulture, encompassing both fruit and vegetable commodities. Prominent fruit crops include Citrus siem, papaya, banana, breadfruit, mangosteen, and durian, among others. Meanwhile, key vegetable commodities include chili, water spinach, long bean, spinach, eggplant, cucumber, and tomato. In 2016, banana was the dominant fruit commodity with a total production of 262,084 quintals, followed by rambutan (85,599 quintals) and papaya (76,864 quintals). For vegetables, chili (both large and bird's eye varieties) recorded the highest production at 30,154 quintals, followed by eggplant at 12,926 quintals.

Beyond its extensive fertile land, Cilacap has also demonstrated agricultural innovation by cultivating rice in marginal lands. Rice cultivation in Cilacap is not only carried out on fertile and productive soils but also on marginal land, including the sandy soils of Sodong Beach. Marginal lands are characterized by low water retention and limited nutrient content, resulting in low fertility. Cultivation on sandy coastal land presents unique challenges and risks, yet it remains possible to grow crops such as rice with proper management. Managing sandy soils requires more intensive efforts than conventional farmland. Substantial additions of organic matter are necessary to improve soil structure and fertility, enabling crops to thrive. The application of organic fertilizers has been shown to improve both soil texture and crop productivity, while studies on sesame cultivation in sandy coastal soils also revealed favorable financial feasibility (Aini et al., 2023; Nurhayati et al., 2013).

The efficient use of production factors is one of the key determinants of successful farming. Inefficient or inappropriate use of inputs often leads to lower productivity and reduced farmer income. Conversely, the precise and efficient use of production inputs generates higher profitability for farmers (Soekartawi, 2013; Aini et al., 2023). These production factors directly influence both production costs and revenues. Farm feasibility is typically measured using the revenue-cost ratio (R/C ratio). If the R/C ratio is less than 1, the farming enterprise is considered unfeasible, whereas values greater than 1 indicate economic feasibility. A preliminary survey in Sodong Beach indicated that rice is cultivated during the first growing season (October–January) and the second growing season (February–May), while farmers switch to secondary crops during the third season (June–September). Interviews with local farmers in Karangbenda Village revealed that average rice productivity on sandy soils reached around 4 tons per hectare of dry harvested grain (GKG) per season.

Overall, this consistent agricultural performance highlights the region's effective utilization of land resources, as reflected in the persistent classification of its agricultural land carrying capacity within Class 1 ($\phi > 2.47$). This classification suggests that Cilacap not only sustains food self-sufficiency but also ensures a decent standard of living for its population. Despite continuous population growth, the steady improvement in agricultural productivity, including innovative uses of marginal land, has successfully kept pace. In doing so, Cilacap maintains a stable rice supply and reinforces regional food security, further strengthening its role as one of Central Java's leading rice barns.

Table 1. Agricultural land carrying capacity

Year	Carrying capacity value	Classification
2013	3.0486	Class 1
2014	3.0002	Class 1
2015	3.3999	Class 1
2016	3.1454	Class 1
2017	3.1961	Class 1
2018	3.3096	Class 1
2019	2.5396	Class 1
2021	2.7346	Class 1
2022	2.5406	Class 1
2023	2.5682	Class 1

However, some degree of fluctuation in agricultural land carrying capacity values was observed between 2019 and 2023, with figures ranging from 2.53 to 2.73. These variations suggest emerging pressures on agricultural land, particularly due to the conversion of farmland into built-up areas driven by population increases and localized changes in productivity. Although still within Class 1, such fluctuations serve as early warnings of potential decline. Should this trend continue without mitigation, Cilacap risks a downgrade to Class 2 ($1 < \phi \leq 2.47$), where food self-sufficiency may persist, but the capacity to support livelihoods could begin to erode.

To sustain its current status and improve agricultural land carrying capacity values beyond 3.0, Cilacap requires proactive interventions. These include implementing stricter land-use regulations to prevent the conversion of productive farmland and introducing strategies to boost agricultural productivity, such as technology adoption and improved farming practices. A relevant concern is highlighted by Naziah et al. (2023), who found that

Dayeuhluhur District is experiencing a decline in youth participation in rice farming. Contributing factors include limited agricultural experience, lower educational attainment, family income disparities, and lack of land ownership. If this trend of declining youth engagement is left unaddressed, it could accelerate the reduction in agricultural land carrying capacity, undermining Cilacap's role as one of Central Java's key rice-producing regions.

3.2 Optimal population size in Cilacap Regency

The sustainability of land carrying capacity ultimately depends on whether existing farmland can meet the population's food needs without compromising future agricultural production. The concept of Optimal Population Size is thus vital in evaluating how many individuals can be supported by the available agricultural land while maintaining food self-sufficiency.

Table 2. Population vs optimal population size

Year	Total population	Optimal population
2013	1,768,502	5,391,505
2014	1,774,649	5,324,469
2015	1,780,533	6,053,744
2016	1,785,971	5,617,636
2017	1,842,913	5,890,290
2018	1,906,849	6,311,010
2019	1,937,427	4,920,333
2021	1,963,824	5,370,291
2022	1,988,622	5,052,408
2023	2,007,829	5,156,607

Analysis of optimal population size in Cilacap Regency from 2013 to 2023 shows that the current population remains within sustainable limits, supported by stable and sufficient rice production levels. This indicates that, for now, the region's agricultural capacity can meet the food demands of its inhabitants. However, rising population density, coupled with signs of stagnation in productivity growth, may soon challenge this balance. If such trends persist, they could lead to a future scenario where population growth surpasses the land's capacity to produce sufficient food, ultimately threatening Cilacap's food security.

In light of these findings, two strategic responses are urgently required. First, urban expansion must be controlled to prevent further encroachment on agricultural land. Second, investment in agricultural modernization such as the adoption of high-yielding crop varieties, precision farming technologies, and sustainable agricultural practices is necessary to enhance productivity per hectare. Without such interventions, Cilacap could face a future food deficit, jeopardizing its established position as a self-sufficient rice-producing region.

The results show that the optimal population size from 2013 to 2023 consistently exceeded the actual population recorded in Cilacap Regency each year. This indicates that the region has made effective use of available open or unused land by converting it into agricultural fields. As a result, the volume of rice harvested has not only been sufficient to meet the food needs of the local population but has also enabled Cilacap to supply rice to other regions, affirming its status as one of Central Java's key rice granaries.

3.3 Population projection, optimal population size, and food demand in 2033

Population projections for the next decade, based on a simple linear regression model, estimate that the total population in Cilacap Regency will reach approximately 5,162,570 by 2033. This represents a significant increase, driven by continuous birth rates and in-migration. Several factors are believed to influence the population growth projections, including economic conditions, public health levels, government policies, availability of residential land, and employment opportunities (Kasikoen, 2010).

Table 3. Linear regression projections of population growth by district in Cilacap Regency

District	Linear regression equation (y = a + bx)
Dayeuhluhur	y = 22.891x - 45,313
Wanareja	y = 22.891x - 45,313
Majenang	y = 22.891x - 45,313
Cimanggu	y = 8.9697x - 17,091
Karangpucung	y = 22.891x - 45,313
Cipari	y = 685x - 1,000,000
Sidareja	y = 750.7x - 1,000,000
Kedungreja	y = 1,183.1x - 2,000,000
Patimuan	y = 517.54x - 996,152
Gandrungmangu	y = 22.891x - 45,313
Bantarsari	y = 9.1117x - 17,663
Kawunganten	y = 701.76x - 1,000,000
Kampung Laut	y = -150.45x + 319,803
Jeruklegi	y = -150.45x + 319,803
Kesugihan	y = -150.45x + 319,803
Adipala	y = 22.891x - 45,313
Maos	y = 22.891x - 45,313
Sampang	y = 22.891x - 45,313
Kroya	y = 22.891x - 45,313
Binangun	y = 22.891x - 45,313
Nusawungu	y = 22.891x - 45,313
Cilacap Selatan	y = 22.891x - 45,313
Cilacap Tengah	y = 22.891x - 45,313
Cilacap Utara	y = 22.891x - 45,313

Based on the land carrying capacity data from 2023 and the population projection for 2033, the corresponding optimal population size can also be estimated. The projected optimal population size suggests that, overall, the existing agricultural land in Cilacap could still support the projected population in 2033. However, disparities at the sub-regency level are apparent. In districts such as South Cilacap, Central Cilacap, and North Cilacap, the projected population exceeds the calculated optimal population size. These findings indicate the need for either expanding agricultural land area or improving rice yields in these areas to ensure that local food demands can be met.

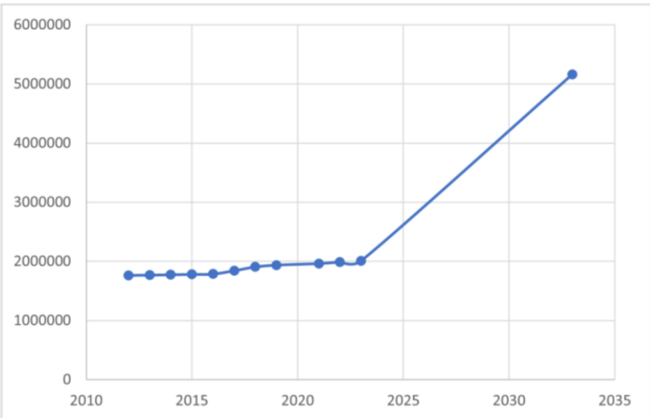

Fig. 2. Population growth chart

Future research should aim to calculate projections of land carrying capacity alongside population projections to produce more accurate estimates. This integration is necessary to anticipate the dynamic interactions between demographic growth, food demand, and agricultural resource availability. Furthermore, the local government is advised to maintain the existing harvested area to ensure food self-sufficiency and preserve Cilacap's reputation as a rice production center. Such policy consistency is critical because shrinking agricultural land, particularly paddy fields, is often the first symptom of development pressure.

Preventing this conversion is not merely a matter of maintaining production capacity but also preserving socio-economic stability for farming households.

Table 4. Projected population, land carrying capacity, and optimal population

District	Projected population 2033	Carrying capacity 2023	Projected optimal population 2033
Dayeuhluhur	48,783	4.61159	224,967
Wanareja	399,753	2.7068	1,082,052
Majenang	162,419	1.99007	323,225
Cimanggu	114,440	2.99645	342,914
Karangpucung	90,559	1.71511	155,319
Cipari	392,605	2.35561	924,823
Sidareja	526,173	1.73771	914,338
Kedungreja	405,242	4.26437	1,728,103
Patimuan	56,007	5.97942	334,889
Gandrungmangu	120,790	3.55799	429,770
Bantarsari	86,109	2.96724	255,506
Kawunganten	426,678	3.95348	1,686,864
Kampung Laut	13,938	6.54393	91,209
Jeruklegi	99,450	1.19343	118,687
Kesugihan	476,659	1.69972	810,186
Adipala	122,440	3.20096	391,925
Maos	44,741	3.50681	156,898
Sampang	53,899	4.01817	216,575
Kroya	444,919	2.0422	908,615
Binangun	244,847	3.31066	810,605
Nusawungu	103,293	2.97809	307,616
Cilacap Selatan	522,310	0.17621	92,035
Cilacap Tengah	100,805	0.43423	43,773
Cilacap Utara	105,711	0.52385	55,377

The agricultural sector plays a crucial role in supporting the economic development of Cilacap Regency. This is evident in the fact that the majority of the population earns a living from farming and depends heavily on agriculture for their livelihood. In 2023, Cilacap experienced significant economic growth in the non-oil and gas sector, reaching 5.76%. Among the contributing sectors, agriculture stood out not only for its quantitative contribution to economic growth but also for its wide-ranging social impact, providing a livelihood safety net and strengthening community resilience. According to data from the Central Statistics Agency of Cilacap Regency in 2024, the agricultural sector accounted for 9.22% of total employment. This figure underscores the importance of agriculture in generating employment opportunities, including for farmers, farm laborers, and small-scale agribusiness entrepreneurs. Moreover, the agricultural sector supports the local economy through farming-related distribution networks and by sustaining traditional markets that are not only places of transaction but also social hubs of rural communities.

These contributions highlight that agriculture in Cilacap is not only a key driver of the local economy but also has a significant impact on community welfare by providing jobs and reinforcing local identity. Therefore, it is imperative to preserve and enhance this sector through modernization of farming systems, innovation, adoption of digital and mechanical technology, and continuous knowledge improvement among farmers and surrounding communities. Such efforts are essential to achieving sustainable agriculture and building a resilient local economy that can withstand both environmental pressures and market fluctuations. This study acknowledges several limitations and calls for future research directions, including the need to project total agricultural carrying capacity more comprehensively. The first limitation concerns the integration of land carrying capacity analysis with the latest paddy field mapping. In practice, mapping paddy fields is analogous to land cover mapping, for which numerous state-of-the-art methods now exist. For example, machine learning on Google Earth Engine has been employed successfully, as shown by studies of Fariz et al. (2024), Amalia et al. (2024), and Fariz et al. (2025a). Simpler methods such as visual interpretation are also still relevant, as demonstrated by Agoes et al. (2018) and Fariz et al. (2025b). More advanced approaches, such as deep learning, have also been introduced in the context of agricultural mapping, for instance by Fariz & Lutfiananda (2025) and Xia et al. (2022).

The availability of increasingly refined mapping methods provides an opportunity to reduce uncertainty in assessing agricultural land carrying capacity. Combining traditional interpretation with machine learning and deep learning may offer hybrid approaches that are both cost-efficient and accurate, enabling planners to capture the heterogeneity of Cilacap's agricultural landscapes. Such advancements would provide more precise baseline data for carrying capacity analysis, improving the reliability of policy interventions. Equally important is the forecasting of future land cover changes using spatial analysis techniques. This methodological advance has been demonstrated in studies by Sidiq et al. (2024), Fariz et al. (2020), and Sujarwo et al. (2022). Land cover data plays a critical role in environmental management and is particularly vital for food security planning (Fariz et al., 2024; Bununu et al., 2023). Anticipating land conversion dynamics allows policymakers to design strategies that proactively safeguard rice self-sufficiency in Cilacap while balancing urban development needs. Without such foresight, the regency risks the gradual erosion of its productive base through uncoordinated land-use change.

Beyond the technical dimension of land mapping, agricultural sustainability also hinges on soil fertility. As Sulakhudin et al. (2025) point out, one of the most important indicators of the sustainability of agricultural cultivation systems is the analysis of soil fertility status, which is the result of complex interactions among physical, chemical, and biological processes in the ecosystem. Wittwer et al. (2021) emphasize that agricultural systems can play multifunctional roles in local ecosystems, including soil conservation, water management, and biodiversity preservation. Similarly, Telo da Gama (2023) argues that agricultural systems can be evaluated through assessments of soil fertility status by utilizing the concept of agricultural ecosystem services. This knowledge is not only relevant for indigenous systems such as the Raja Uncak rice cultivation in Kapuas Hulu but also crucial for more intensive rice systems in Cilacap. Viana et al. (2022) highlight how indigenous agricultural systems, when studied integratively with soil fertility and biodiversity, can provide adaptive and sustainable strategies for managing land resources. Thus, the assessment of soil fertility in Cilacap's agricultural landscapes is not merely a technical requirement but a strategic necessity. Ensuring soil productivity is the bedrock for long-term resilience of food systems, particularly under programs like IP 400, which increase cropping intensity but risk soil nutrient depletion if not accompanied by integrated soil fertility management. By embedding soil monitoring into local agricultural policy, Cilacap can avoid the ecological trap of short-term productivity gains that undermine long-term carrying capacity.

This connects directly with the findings of Hidayat et al. (2023), who analyzed the characteristics of farmers participating in the IP 400 program in Cilacap. Their study revealed that demographic factors such as age, education, farming experience, land size, and economic access significantly affect farmers' competencies in adopting and implementing technological innovations (Prajatino et al., 2021). The majority of farmers in the program are within productive age (84.38%), meaning they have both the physical strength and the maturity to adopt new agricultural practices. However, challenges remain in terms of education. As reported, most farmers have only completed primary education (65.62%), followed by junior high (25.25%) and senior high (9.37%). This relatively low education level affects their ability to quickly adopt innovations, necessitating strong extension services and continuous training. Landholding size also emerged as a critical variable. Most farmers involved in the IP 400 program operate on plots smaller than 0.5 ha, reflecting the widespread phenomenon of petani gurem in Indonesia (Minarsih et al., 2023). Limited landholding reduces economies of scale and makes it more difficult for farmers to invest in advanced technology or absorb risks. Nonetheless, long farming experience, with 57.81% of farmers having more than 20 years in farming, provides a compensatory strength.

Experience translates into tacit knowledge about soil, climate, and crop behavior, enabling better decision-making in managing risks.

From a production perspective, farmers under IP 400 achieved yields between 3–5 tons/ha per season, slightly lower than the Cilacap average of 6.3 tons/ha (Cilacap Regency Office of the Department of Agriculture, 2021). This decline in per-harvest productivity is attributable to the absence of land rest periods, leading to greater pest and disease incidence. Nevertheless, when aggregated annually, the total yield per hectare reaches 16 tons due to four harvests, surpassing the 15 tons obtained under the conventional IP 300 system. Thus, despite per-season losses, the cumulative annual output suggests higher food availability, though at the expense of soil health and long-term sustainability. Economically, farmers' income under IP 400 averaged Rp 21.7 million per hectare per season, translating to about Rp 2.17 million per month, slightly below the local minimum wage (UMR Cilacap 2021). This finding underlines that despite increased harvest frequency, structural issues such as high input costs (fertilizer, pesticide, labor) continue to suppress net income. As Supartama et al. (2013) argue, farmer income is influenced not only by yields and selling price but also by the burden of production costs. Therefore, improving farmers' profitability requires systemic interventions: efficient input use, collective marketing, and perhaps subsidies for sustainable practices. At the institutional level, the role of farmer groups in the IP 400 program was assessed as moderate in terms of functioning as learning forums and cooperation units (Nuryanti & Swastika, 2011). While farmer groups facilitated access to training, inputs, and machinery, their role in post-harvest processing and marketing remained weak. Strengthening these groups is vital, as they embody the principle of "from and for farmers" and can serve as platforms for collective bargaining, risk sharing, and innovation diffusion. Integrating post-harvest value addition, storage, and marketing into farmer group functions could transform them into true agents of rural economic resilience.

Taken together, the lessons from IP 400 in Cilacap reveal a paradox: on the one hand, higher cropping intensity increases short-term food supply, but on the other, it risks long-term soil fertility decline and farmer income stagnation. The integration of soil fertility monitoring (Sulakhudin et al., 2025) with farmer-centered socio-economic analysis (Hidayat et al., 2023) is therefore essential. Only by aligning ecological carrying capacity with farmer livelihoods can sustainable food security be achieved. The findings also resonate strongly with global sustainability frameworks, particularly the Sustainable Development Goals (SDGs). SDG 2 (Zero Hunger) directly addresses the eradication of hunger and the achievement of food security, both of which are tied to sustainable rice production. In Cilacap, balancing productivity gains with ecological limits is crucial for ensuring that food availability is maintained without compromising future capacity. SDG 12 (Responsible Consumption and Production) emphasizes efficiency and sustainability in agricultural systems, including reducing post-harvest losses. For Cilacap, this means strengthening supply chain infrastructure and farmer groups to minimize waste and enhance profitability. SDG 13 (Climate Action) acknowledges the need to build resilience in agricultural sectors against climate variability. Given the exposure of Cilacap's coastal and lowland areas to climate shocks, adaptation through crop diversification, water management, and soil fertility strategies becomes a matter of survival. Finally, SDG 15 (Life on Land) underscores the importance of preserving ecosystems and preventing land degradation. By integrating soil fertility assessment with land cover mapping, Cilacap can ensure that agricultural intensification does not degrade the very land base on which its future depends.

In conclusion, future agricultural development in Cilacap must be based on a triadic integration of spatial analysis of land use, soil fertility assessment, and farmer socio-economic empowerment. Land cover forecasting will ensure that paddy fields are preserved amidst development pressures (Fariz et al., 2024; Bununu et al., 2023). Soil fertility monitoring will safeguard long-term productivity and ecological balance (Sulakhudin et al., 2025; Wittwer et al., 2021). Farmer group empowerment and tailored extension services will bridge the gap between innovation and practice (Hidayat et al., 2023). The synergy among these three pillars—ecology, economy, and society—will determine Cilacap's capacity to remain a rice production center and secure its people's welfare. Importantly, situating Cilacap's agricultural challenges within the framework of the SDGs demonstrates that local food security is inseparable from global sustainability goals. By aligning its agricultural development with SDG 2, SDG 12, SDG 13, and SDG 15, Cilacap not only secures its role as a rice barn for Central Java but also contributes meaningfully to the global fight against hunger, climate change, and ecosystem degradation.

4. Conclusions

The findings of this study demonstrate that the agricultural land carrying capacity in Cilacap Regency, for both lowland and upland rice, consistently fell into Class 1 from 2013 to 2023. This classification reflects a condition of agricultural abundance, in which the region not only meets its own food needs but also generates a surplus that contributes to the food security of neighboring regencies. Such results reaffirm Cilacap's long-standing reputation as one of Central Java's rice granaries, emphasizing its strategic role in ensuring regional food self-sufficiency. The analysis of optimal population size further strengthens this conclusion, as calculated values consistently exceeded the actual population over the observed decade. This indicates that agricultural resources have been effectively managed, with open and underutilized land mobilized for production, illustrating the adaptability of Cilacap's agricultural sector in balancing demographic pressures with food provision. Looking toward 2033, however, a more complex picture emerges. While Cilacap has thus far sustained its capacity, projected population growth raises concerns about future vulnerabilities. Several sub-districts—particularly South, Central, and North Cilacap—are expected to experience mismatches between population growth and carrying capacity. If agricultural land expansion or productivity improvement does not keep pace, the regency may struggle to maintain its surplus status. This underscores the need for proactive interventions to strengthen agricultural resilience amid demographic change. Agriculture in Cilacap is not only about food production but also about broader economic and social development. Farmland provides livelihoods for a large portion of the population, directly and indirectly, through farming, processing, and distribution. These activities create multiplier effects across the local economy, support traditional markets, and reinforce social cohesion. Thus, sustaining productivity ensures not only food availability but also economic stability and rural welfare.

To secure the future of agricultural land carrying capacity, several strategies are essential. Expanding the harvested area in underutilized zones may temporarily reduce pressure, but such expansion has limits due to competing demands for housing, infrastructure, and industry. Therefore, sustainable pathways emphasize agricultural intensification, including the adoption of high-yield rice varieties, improved irrigation, precision agriculture, and enhanced soil management. Investments in agricultural research and extension services will be crucial to enable farmers to adopt climate-resilient practices. Addressing post-harvest inefficiencies is another key measure. Losses at harvesting, storage, and distribution stages significantly reduce effective availability. Improving infrastructure, storage technologies, and supply chain management would increase the usable rice supply without requiring additional farmland. Similarly, integrating population management and land-use planning into development policy is necessary to anticipate demographic growth while safeguarding agricultural land from excessive conversion. Strategic zoning, farmland preservation incentives, and community-based stewardship could protect Cilacap's agricultural base.

Finally, strengthening the socio-economic dimension of agriculture ensures that productivity gains translate into inclusive development. Empowering farmer groups, cooperatives, and local institutions, alongside improved access to credit, training, and markets, will enhance resilience, reduce inequality, and promote sustainable livelihoods. In conclusion, Cilacap Regency has shown strong capacity to sustain agricultural land carrying capacity over the past decade. Yet, demographic pressures projected for 2033 highlight the urgency of proactive planning and investment. By combining efficient land use, technological innovation, post-harvest management, and socio-economic empowerment, Cilacap can secure its role as a vital rice-producing hub in Central Java. Ultimately, sustaining agricultural land carrying capacity is not only about ensuring food supply but also about safeguarding economic stability, community well-being, and long-term regional resilience.

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Author Contribution

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