Development of the agricultural sector based on an ecological footprint approach to support food security in Jombang Regency, East Java, Indonesia

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Abstract. This study examines the development of the agricultural sector in Jombang Regency, East Java, Indonesia, using the ecological footprint approach to support sustainable food security. The research aims to assess the balance between human demand for natural resources and the ecological capacity that sustains agricultural activities, while also projecting future conditions through forecasting and spatial analysis. Agriculture plays a crucial role in meeting food needs and supporting local livelihoods, yet its sustainability is increasingly threatened by land limitations, environmental degradation, and the continual conversion of agricultural areas. Jombang Regency, as one of East Java's key food-producing regions, faces pressures from intensification practices that risk reducing soil quality, water availability, and biodiversity. This study measures biocapacity and ecological footprint to evaluate agricultural land availability and utilization, supported by projection models to identify long-term trends. Findings show a decline in biocapacity from 2022 to 2024, with several subdistricts experiencing ecological deficits. Projections to 2044 indicate a continued decrease in ecological capacity. These results serve as a foundation for strategies to strengthen agricultural surplus through integrated agro-industry development and sustainable regional planning. The ecological footprint approach offers a robust analytical basis for maintaining Jombang's role as a regional food basket.

1 Introduction

Agriculture is a sector that plays a crucial role in ensuring the sustainability of human life, particularly as a food provider and a pillar of the regional economy. In the context of regional development, the utilization of natural resources must be balanced to support growth and efficiency without compromising environmental sustainability [1]. However, the dynamics of development and pressures on spatial use often create a mismatch between development needs and the region's ecological capacity.

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One phenomenon of concern in Jombang Regency is the massive conversion of agricultural land to non-agricultural uses. The annual decline in agricultural land, which reaches approximately 6 percent, is influenced by weak spatial utilization controls and the lack of a Sustainable Food Agricultural Land (LP2B) policy [2]. Data from the Jombang Statistics Agency (BPS) shows that over the past ten years, agricultural land has decreased by 867 hectares and production has decreased by 17,893 tons, indicating significant pressure on regional food production capacity [3]. These trends are consistent with recent findings showing that spatial and temporal land-use transitions in Jombang have contributed to a gradual decline in agricultural land carrying capacity, particularly in areas exposed to rapid settlement expansion and industrial development [4].

On the other hand, Jombang Regency has been designated by central government policy as one of the regions targeted for food self-sufficiency. To achieve this goal, an analytical approach is needed that can assess the region's ability to provide adequate land resources. The Ecological Footprint (EF) approach is a relevant method because it calculates the balance between human demand for land resources and the region's ecological capacity to meet them [5]. EF measures three main components: biocapacity, ecological footprint, and environmental carrying capacity, thus illustrating the surplus or deficit of a region's agricultural sector.

Several previous studies have shown that EF analysis can be used as a basis for formulating policies for land management and sustainable agricultural development [6]. This method can also be combined with forecasting techniques such as Exponential Triple Smoothing [7] and spatial modeling based on Artificial Neural Networks and Cellular Automata [8] to project future changes in ecological capacity. However, international literature indicates that integrated approaches combining ecological footprint, climate-related productivity analysis, and spatial transformation modeling are still limited, particularly in the context of agricultural regions under climate stress [9]. This establishes a clear research gap where EF-based assessments rarely incorporate climate vulnerability and long-term spatial change dynamics simultaneously.

Moreover, the IPCC emphasizes that localized climate risk assessments are crucial at the subregional scale, yet empirical studies at the district level, especially in Southeast Asia, remain scarce [10]. This research therefore contributes both conceptually and empirically by integrating EF assessment, spatial modeling, and production forecasting to address climate-related ecological risks in a rapidly developing agricultural region.

Given these pressures and potential, a comprehensive analysis is needed to evaluate the carrying capacity of agricultural land across all districts in Jombang Regency. In addition to assessing existing conditions, projections of future land capacity are also needed to anticipate the risk of ecological deficits. The results of this analysis are then formulated into guidelines for agricultural sector development, considering stakeholder perspectives, so that the resulting policies are more contextual and aligned with community needs.

Thus, the novelty of this research lies in its integrated methodological framework, combining ecological footprint analysis, climate-relevant interpretations of biocapacity trends, long-term agricultural production forecasting, and spatial land-use change modeling. This approach provides a multidimensional understanding of ecological capacity that is rarely addressed simultaneously in existing studies, positioning this research as a valuable contribution to agricultural sustainability analysis at the regional scale.

This research aims to provide an overview of the relationship between agricultural development, the ecological footprint, and food security in Jombang Regency. This analysis not only provides an understanding of existing conditions but can also serve as a basis for policy recommendations for sustainable agricultural development. Thus, Jombang Regency can continue to maintain its role as a regional food barn while ensuring the sustainability of natural resources for future generations.

2 Method

At the analysis method stage, biocapacity and ecological footprint calculations were carried out to determine the land's ability to provide agricultural resources and the amount of ecological consumption needed by the community in Jombang Regency. Biocapacity calculations were carried out to describe the ecological capacity of the land to support human activities, as explained that biocapacity is one of the fundamental components of ecological footprint analysis used to measure the ability of a region to meet the biological needs of its population [6]. In this study, biocapacity was calculated by considering the land area of each sector, yield factors, and equality factors, so that the resulting value reflects the ecological potential of the agricultural sector based on the productivity and characteristics of the land owned by Jombang Regency. The calculation follows the formula from [5], namely:

$$BC=A\times YF\times EQF \quad (1)$$

where:

BC is Biocapacity (gha); A is the land area of the sector (ha); YF is the yield factor for a specific sector; EQF is the equivalence factor based on land type.

Meanwhile, an ecological footprint analysis is conducted to determine the extent of land consumption required by the community for each analyzed sector. According to [11], the ecological footprint is a measure of the amount of productive land required to meet community consumption patterns, including food needs from the agricultural sector. In the context of this research, the ecological footprint value is calculated using total consumption data per sector, considering regional productivity, yield factors, and equivalence factors, thus illustrating the level of community consumption pressure on ecological resources.

$$EF=(P/YKL)\times YF\times EQF \quad (2)$$

where:

EF is the ecological footprint (gha); P is the total consumption/production of the sector; YKL is the productivity in the study area; YF and EQF are the same as in the biocapacity calculation.

The results of the biocapacity and ecological footprint calculations are then used to obtain an ecological carrying capacity value. This capacity is calculated through a direct comparison between biocapacity and the ecological footprint, providing information on whether a sector is experiencing a carrying capacity surplus or deficit. A value greater than one indicates that a sector can meet the community's ecological needs (surplus), while a value less than one indicates that the land is unable to meet these needs (deficit). This assessment is used to understand the carrying capacity of agricultural land in each district in Jombang Regency and to identify which districts are under high consumption pressure due to declining land capacity.

In addition, this study also conducted data projections to estimate the development of agricultural production volume, population, and ecological parameters such as yield factor (YF), national yield factor (YFN), world yield factor (YFW), and equivalence factor (EQF) in the future period. The forecasting technique used is Exponential Triple Smoothing, a time series smoothing method that combines level, trend, and seasonal components to produce stable predictions and can follow data change patterns more accurately than single or double smoothing methods [7]. This method utilizes value updates based on historical pattern structures so that projections of ecological and production conditions can be described up to two decades into the future.

a. Level smoothing

$$S'_t=\alpha X_t+(1-\alpha)S'_{t-1} \quad (3)$$

b. Trend smoothing

$$S''_t=\beta(S'_t-S'_{t-1})+(1-\beta)S''_{t-1} \quad (4)$$

c. Seasonal smoothing

$$S'''_t=\gamma(X_t-S'_t)+(1-\gamma)S'''_{t-1} \quad (5)$$

d. Forecasting equation

$$F_{t+m}=S'_t+mS''_t+0.5m^2S'''_t \quad (6)$$

In addition to tabular projections, this study also included land cover change modeling using the MOLUSCE plugin in QGIS. This model combines cellular automata (CA) and artificial neural networks (ANN). CA simulates spatial changes based on cell transition rules and environmental influences, while ANN is used to learn historical land cover change patterns through a weight mechanism and the network's ability to recognize nonlinear data structures [8]. The integration of these two methods allows the model to produce land cover change projection maps that more closely approximate actual conditions and support spatial assessments of ecological carrying capacity.

In addition to the series of analytical techniques used, this study is also supported by a set of indicators describing the biophysical, social, and spatial use conditions in Jombang Regency. These indicators are shown in Table 1. Population data is used to represent ecological consumption pressure, while the area of agricultural land, livestock, forestry, and built-up land reflects the availability of ecological resources in each sector. Agricultural productivity is analyzed to understand the potential yields of each commodity, while slope, river presence, distance to built-up land, and distance to road networks are used as spatial variables that play a role in shaping land cover change patterns.

Table 1. Research Dimensions and Indicators.

Dimension	Indicator
Population	Quantity of Population
Land Availability	Agricultural Land Area
	Livestock Land Area
	Forestry Land Area
	Built-Up Land Area
Land Productivity	Agricultural Sector Productivity
	Livestock Sector Productivity
	Forestry Sector Productivity
Production	Agricultural Production
	Livestock Production
	Forestry Production

3 Results and Discussion

3.1 Existing Biocapacity and Ecological Footprint

The analysis indicates that the biocapacity of the agricultural sector in Jombang Regency experienced a decline between 2022 and 2024. This reduction is closely related to the ongoing conversion of agricultural land into non-agricultural uses, which directly diminishes the availability of productive land and weakens the ecological capacity needed to sustain

agricultural activities. The expansion of built-up areas also contributes to land fragmentation, lowering cultivation efficiency and increasing production costs for farmers. In addition to spatial conversion, soil degradation, decreased water availability, and declining micro-biodiversity further erode land productivity. These findings align with broader regional studies showing that land conversion is a principal driver of declining agricultural ecological capacity, especially in areas facing rapid development pressures [12]. Overall, the continued decrease in biocapacity signals growing vulnerability in the sustainability of food production across the regency.

Furthermore, the expansion of built-up land tends to increase land fragmentation, causing agricultural land blocks to become increasingly separate and smaller, thus reducing cultivation efficiency and increasing farmers' production costs. Furthermore, other factors driving the decline in biocapacity are declining land productivity due to soil degradation and the decline in the quality of the supporting environment, such as the availability of irrigation water, soil quality, and microbiodiversity that plays a role in soil fertility. This condition is exacerbated by the reliance on intensive agricultural systems that exploit land without adequate ecological restoration, thus reducing the long-term carrying capacity of the agricultural sector. In this context, the decline in biocapacity indicates increasing vulnerability to instability in regional food production, especially in districts with the highest development pressures.

The ecological footprint analysis reveals significant variations across districts during the same period. Mojowarno exhibited the highest ecological footprint in 2024 due to its substantial agricultural output, while Wonosalam recorded the lowest footprint because of its limited agricultural land and lower production levels. When biocapacity is compared to ecological footprint, six districts were identified as being in a deficit condition in 2024, while others remained in surplus but showed declining ecological capacity trends. These contrasts highlight how differences in land productivity, agricultural intensity, and exposure to spatial development pressures shape the ecological dynamics across subregions. Comparable spatial disparities have been reported in other studies, which emphasize that variations in land productivity and land-cover transitions can lead to uneven ecological pressures and differentiated sustainability challenges among districts [13]. These district-level differences are clearly summarized in Table 2, which presents the biocapacity, ecological footprint, and resulting land capacity status for each district, supporting the observed variation in ecological performance. This underscores the importance of district-specific resource management strategies.

Table 2. Existing Biocapacity and Ecological Footprint in Agricultural Sector

District	Biocapacity		Ecological Footprint		Land Capacity	
	2022	2024	2022	2024	2022	2024
Bandar Kedung Mulyo	6,636.35	6,587.59	6,636.35	6,587.59	1.00	1.00
Perak	5,192.53	5,184.46	7,578.41	6,888.57	0.69	0.75
Gudo	6,912.26	6,844.67	7,772.65	7,575.27	0.89	0.90
Diwek	7,926.41	7,697.07	6,012.61	6,921.70	1.32	1.11
Ngoro	9,386.11	9,204.04	7,716.15	8,700.44	1.22	1.06
Mojowarmo	11,333.05	11,326.81	10,672.91	11,783.57	1.06	0.96
Bareng	12,108.71	12,315.11	6,238.46	5,890.68	1.94	2.09
Wonosalam	1,674.52	1,862.82	174.32	238.84	9.61	7.80
Mojoagung	6,187.57	6,124.93	4,836.16	4,730.99	1.28	1.29
Sumobito	9,093.38	8,891.97	9,615.30	7,992.76	0.95	1.11
Jogoroto	4,440.34	4,296.69	2,764.06	3,234.99	1.61	1.33

District	Biocapacity		Ecological Footprint		Land Capacity	
	2022	2024	2022	2024	2022	2024
Peterongan	4,951.95	4,780.38	5,503.22	5,295.09	0.90	0.90
Jombang	4,623.28	4,541.08	5,282.53	5,133.84	0.88	0.88
Megaluh	6,348.21	6,299.27	6,119.26	6,120.96	1.04	1.03
Tembelang	6,269.24	6,149.04	7,080.86	7,502.65	0.89	0.82
Kesamben	11,059.32	10,882.79	9,253.44	7,886.45	1.20	1.38
Kudu	5,166.82	4,862.26	2,131.52	2,594.39	2.42	1.87
Ngusikan	5,013.85	5,171.32	2,847.01	2,528.40	1.76	2.05
Ploso	5,360.90	5,278.28	4,118.96	3,574.33	1.30	1.48
Kabuh	13,625.54	14,111.58	4,153.65	4,486.62	3.28	3.15
Plandaan	8,839.32	9,030.82	5,732.67	4,549.30	1.54	1.99

3.2 Projection of Agricultural Production in 2044

Projections on agricultural production in Jombang Regency show that there are quite significant differences between districts until 2044. Based on the results of calculations using the Exponential Triple Smoothing method, Bandar Kedung Mulyo district is projected to be the region with the highest agricultural production, namely 53,459.52 tons in 2044. The high production value in this district is inseparable from the vast remaining productive agricultural land and the high level of agricultural intensification that has been taking place consistently in recent years. Meanwhile, the district with the lowest production projection is Wonosalam, which only reaches 25.42 tons in 2044. The low production value in this district is influenced by the biophysical conditions of the region which are dominated by hills, so that the availability of agricultural land is relatively limited and its productivity is not as high as other districts in the lowlands. In addition to the physical condition of the land, the relatively low level of land conversion also causes cultivation space to not experience significant expansion, so that its production capacity remains small throughout the projection period. These differences across districts are clearly reflected in Table 3, which presents the projected agricultural production value for each district from 2029 to 2044 and illustrates the widening gap between high-producing and low-producing areas. It shows a contrast between topographically constrained zones and low-land agricultural areas, where slope, land availability, and physiographic constraints consistently suppress long-term yield potential [14,15].

Table 3. Agricultural Sector Production Projection Year 2029–2044

District	Agricultural Sector Production Projection			
	2029	2034	2039	2044
Bandar Kedung Mulyo	38,162.46	40,311.45	51,310.53	53,459.52
Perak	21,635.12	18,074.98	14,514.83	10,954.69
Gudo	31,054.86	33,906.21	36,757.57	39,608.92
Diwek	22,412.18	16,987.17	19,598.61	14,173.60
Ngoro	24,150.76	16,249.70	13,830.15	5,929.08
Mojowarmo	44,231.83	41,751.87	45,305.37	42,825.42
Bareng	19,184.68	13,661.34	8,138.01	2,614.67
Wonosalam	651.62	442.89	234.15	25.42
Mojoagung	15,219.66	11,738.23	10,845.50	7,364.07
Sumobito	26,265.57	21,805.82	17,346.06	12,886.30

District	Agricultural Sector Production Projection			
	2029	2034	2039	2044
Jogoroto	11,009.75	10,877.50	10,745.26	10,613.01
Peterongan	18,513.09	17,731.20	16,949.31	16,167.42
Jombang	16,997.69	14,520.99	13,031.30	10,554.60
Megaluh	20,962.10	17,910.57	17,859.92	14,808.39
Tembelang	28,018.10	26,554.26	27,996.70	26,532.86
Kesamben	34,865.75	29,999.93	31,681.54	26,815.72
Kudu	9,423.95	9,597.69	9,771.43	9,945.17
Ngusikan	11,499.16	13,203.24	14,907.33	16,611.41
Ploso	12,045.92	8,477.97	6,821.95	3,254.00
Kabuh	16,744.02	17,654.39	18,564.77	19,475.14
Plandaan	14,423.76	12,035.61	9,647.46	7,259.32

In general, the projection results indicate that districts with extensive land capacity and relatively stable productivity tend to experience higher production increases than areas with more limited biophysical characteristics. This increase is not solely influenced by land area, but also determined by each district's ability to maintain land quality, the availability of supporting agricultural infrastructure, and the sustainability of implemented cultivation practices. Districts such as Bandar Kedung Mulyo, which have a combination of extensive productive land and adequate irrigation support, consistently show a significant trend of production increases until 2044. Conversely, districts with challenging topographical conditions, such as Wonosalam and Bareng have physical limitations that easily limit production capacity increases, even though some of them have good soil quality.

The projection pattern also shows that production growth is not occurring evenly across the Jombang. Areas with high land conversion pressure tend to experience slow production growth or even potential stagnation in the long term. This unequal distribution of production has the potential to create an imbalance in the agricultural structure, with certain districts becoming the main production centers, while others serve only as buffer zones with minimal contributions. The spatial projection of agricultural production can be seen in Figure 1.

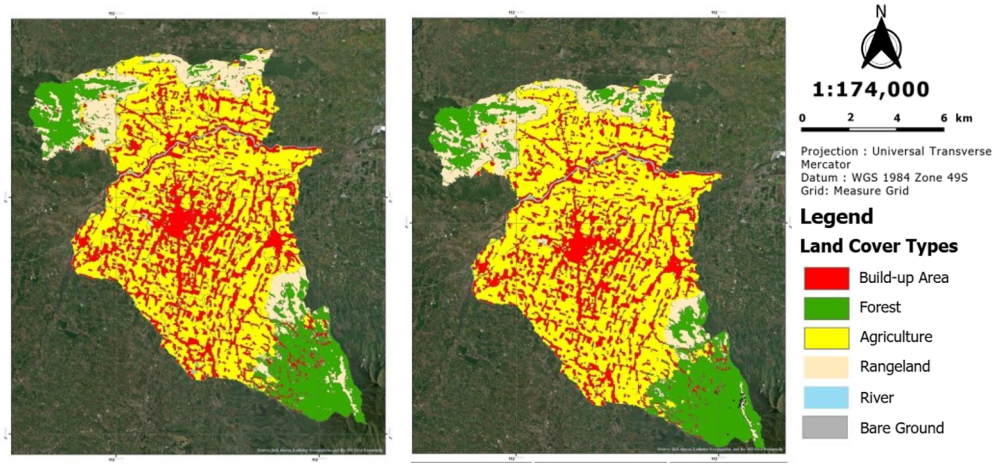

Fig. 1. Land Use Changes in Jombang Regency 2024 and 2044

3.3 Projection of Biocapacity and Ecological Footprint (2029–2044)

The analysis shows that the biocapacity value of the agricultural sector in all districts of Jombang Regency is expected to increase during the period 2029 to 2044. This increase is the result of calculations of productivity projections and changes in land area based on the ETS method and the MOLUSCE-based land change model. This finding indicates that theoretically, the ecological capacity of the region to provide agricultural resources is maintained, although in some districts, the increase is not very significant. The distribution of these projected biocapacity values for each district is presented in Table 4, which clearly shows gradual increases across most areas, along with notable variations in the magnitude of change between districts.

Table 4. Agricultural Sector Biocapacity Projection 2029–2044

District	Biocapacity Projection of the Agricultural Sector			
	2029	2034	2039	2044
Bandar Kedung Mulyo	6,681.41	6,714.65	6,742.87	6,766.47
Perak	5,384.26	5,419.63	5,450.81	5,478.17
Gudo	7,147.14	7,188.39	7,223.86	7,255.43
Diwek	8,405.21	8,487.30	8,553.44	8,613.28
Ngoro	9,783.93	9,847.07	9,901.64	9,946.89
Mojowarmo	11,571.51	11,655.40	11,726.95	11,783.65
Bareng	11,898.65	11,965.37	12,022.53	12,069.04
Wonosalam	1,653.40	1,662.35	1,669.45	1,675.02
Mojoagung	6,524.18	6,579.42	6,623.66	6,664.52
Sumobito	9,357.37	9,410.61	9,455.07	9,497.17
Jogoroto	4,721.48	4,762.55	4,796.44	4,824.02
Peterongan	5,145.92	5,183.74	5,217.38	5,246.20
Jombang	4,927.30	4,966.64	5,001.85	5,030.50
Megaluh	6,449.84	6,476.23	6,498.62	6,517.24
Tembelang	6,378.65	6,411.99	6,441.91	6,465.30
Kesamben	11,177.50	11,227.43	12,965.64	11,305.82
Kudu	5,090.84	5,117.16	5,139.68	5,158.04
Ngusikan	5,103.10	5,129.11	5,149.44	5,165.40
Ploso	5,534.69	5,563.04	5,586.68	5,607.37
Kabuh	12,890.60	12,976.82	13,048.75	13,108.38
Plandaan	8,708.40	8,758.26	8,798.63	8,831.50

However, the ecological footprint projections show a different pattern. The agricultural sector's ecological footprint varies across districts, with some areas experiencing a decline in ecological consumption and others experiencing an increase due to changes in production and consumption needs. Bandar Kedung Mulyo again holds the position of the region with the highest Ecological Footprint value in 2044, at 11,932.65, an increase compared to 2029. This condition occurs because the district has a high production volume and intensive agricultural activities, resulting in increased ecological consumption needs. Conversely, districts such as Perak, Diwek, and Ngoro show a decline in ecological footprint as their production or consumption trends decline. These projected differences across districts are detailed in Table 5, which presents the ecological footprint values from 2029 to 2044 and

illustrates how consumption pressures diverge over time among regions with varying agricultural intensities.

Table 5. Ecological Footprint Projection of the Agricultural Sector 2029–2044

District	Ecological Footprint Projection of the Agricultural Sector			
	2029	**2034**	**2039**	**2044**
Bandar Kedung Mulyo	9,823.94	9,875.60	11,987.30	11,932.65
Perak	5,569.40	4,428.05	3,390.99	2,445.19
Gudo	7,994.27	8,306.43	8,587.40	8,841.07
Diwek	5,769.44	4,161.56	4,578.68	3,163.68
Ngoro	6,216.99	3,980.89	3,231.03	1,323.42
Mojowarmo	11,386.34	10,228.48	10,584.36	9,559.02
Bareng	4,938.60	3,346.79	1,901.22	583.62
Wonosalam	1,653.40	1,662.35	1,669.45	1,675.02
Mojoagung	3,917.91	2,875.66	2,533.75	1,643.73
Sumobito	6,761.39	5,342.04	4,052.43	2,876.34
Jogoroto	2,834.17	2,664.80	2,510.33	2,368.92
Peterongan	4,765.72	4,343.83	3,959.74	3,608.72
Jombang	4,375.61	3,557.39	3,044.40	2,355.88
Megaluh	5,396.15	4,387.78	4,172.48	3,305.37
Tembelang	7,212.54	6,505.33	6,540.66	5,922.38
Kesamben	8,975.29	7,349.46	7,401.52	5,985.51
Kudu	2,425.95	2,351.27	2,282.83	2,219.85
Ngusikan	2,960.16	3,234.56	3,482.69	3,707.82
Ploso	3,100.91	2,076.95	1,593.76	726.32
Kabuh	4,310.31	4,325.02	4,337.15	4,347.03
Plandaan	3,713.02	2,948.51	2,253.87	1,620.35

3.4 Projection of Land Carrying Capacity in 2044

The projection of the land carrying capacity of the agricultural sector shows increasingly diverse dynamics between districts in Jombang Regency until 2044. Based on the previously projected calculations of biocapacity and ecological footprint values, it appears that not all districts can maintain a surplus condition in the future. Two districts, namely Bandar Kedung Mulyo and Mojowarno, are projected to experience a land carrying capacity deficit in 2044. This condition indicates that the ecological needs of the community in both areas exceed the ecological capacity of the available land. In Bandar Kedung Mulyo, this deficit is in line with the very high increase in the ecological footprint to reach 11,932.65 gha in 2044, while its biocapacity does not show significant growth to balance the increase in ecological needs. Detailed findings regarding the carrying capacity status per district can be seen in Table 6.

Table 6. Projection of the Carrying Capacity of the Agricultural Sector 2029–2044

District	Projection of the Carrying Capacity of the Agricultural Sector				
	2029	2034	2039	2044	Status
Bandar Kedung Mulyo	0.17	0.17	0.14	0.14	Deficit
Perak	1.17	1.49	1.95	2.73	Surplus
Gudo	1.17	1.13	1.10	1.07	Surplus Decreasing
Diwek	0.82	1.14	1.05	1.52	Surplus
Ngoro	0.83	1.30	1.61	3.96	Surplus
Mojowarmo	0.43	0.49	0.47	0.53	Deficit
Bareng	1.31	1.94	3.42	11.17	Surplus
Wonosalam	1.00	1.00	1.00	1.00	Surplus
Mojoagung	2.85	3.90	5.12	6.88	Surplus
Sumobito	0.75	0.96	1.27	1.79	Surplus
Jogoroto	1.80	1.92	2.05	2.18	Surplus
Peterongan	1.16	1.28	1.41	1.55	Surplus
Jombang	2.95	3.65	4.29	5.56	Surplus
Megaluh	1.61	2.00	2.11	2.67	Surplus
Tembelang	0.88	0.99	0.98	1.09	Surplus
Kesamben	1.25	1.53	1.75	1.89	Surplus
Kudu	2.10	2.18	2.25	2.32	Surplus
Ngusikan	1.72	1.59	1.48	1.39	Surplus Decreasing
Ploso	1.78	2.68	3.51	7.72	Surplus
Kabuh	2.99	3.00	3.01	3.02	Surplus
Plandaan	2.35	2.97	3.90	5.45	Surplus

In addition to the districts entering a deficit, several other districts, such as Gudo and Ngusikan, are showing a worrying downward trend in their carrying capacity. Although these districts have maintained surplus status in previous years, projections of carrying capacity trends indicate a potential change in status if land management interventions and productivity increases are not implemented. In Gudo district, the increase in ecological footprint, unmatched by growth in biocapacity, is causing additional pressure on agricultural land. Meanwhile, Ngusikan district, despite experiencing increased biocapacity, is experiencing a trend of increasing ecological consumption in line with increasing productivity, making it vulnerable to entering a deficit category in the coming decades. Meanwhile, Ngusikan district, despite experiencing increased biocapacity, is experiencing a trend of increasing ecological consumption in line with increasing productivity, making it vulnerable to entering a deficit category in the coming decades.

On the other hand, areas like Wonosalam district are showing a relatively stable pattern, with a balanced carrying capacity between biocapacity and ecological footprint. However, while this balance appears positive, both values are at low levels. The small area of agricultural land and limited production capacity mean that this stable carrying capacity does not fully reflect a safe condition for agricultural sustainability. The resulting balance is more due to low ecological consumption than to increased land capacity.

3.5 Implications for Agricultural Development and Spatial Planning

The results of the analysis of biocapacity projections, ecological footprints, and land carrying capacity until 2044 indicate that Jombang Regency is facing increasingly complex ecological

pressures, especially in districts with high levels of agricultural activity and rapid land conversion rates. The projected deficit conditions in Bandar Kedung Mulyo and Mojowarno districts indicate an imbalance between available ecological capacity and community ecological consumption. This imbalance indicates that production intensity that is not balanced with ecological recovery has pushed the region beyond the carrying capacity limit. This condition is in line with warnings [5] regarding the ecological consequences if consumption exceeds the land's regenerative capacity,and is also supported by [4], who found that spatial and temporal land-use transitions in Jombang have progressively diminished agricultural land carrying capacity, particularly in districts experiencing accelerated settlement and industrial expansion.

The implications of this situation demonstrate that agricultural development can no longer be solely oriented toward expanding production. Jombang Regency needs to adopt an agricultural development strategy that integrates ecological dimensions into every planning process. Districts with potential deficits require stronger policy interventions, such as restoring soil productivity, conserving water catchment areas, increasing irrigation efficiency, and implementing low-input farming systems to maintain ecosystem sustainability. At the same time, districts with high surpluses, such as Wonosalam, Kabuh, and Bareng districts, need to be encouraged to become ecological buffer zones and strengthen regional food security through optimizing land use and developing superior value-added commodities.

In line with these implications, regional grouping is needed as a basis for formulating a more targeted strategy. The clusters are arranged based on the suitability between the ecological conditions of each district and the development directions outlined previously. The grouping is carried out by considering trends in biocapacity changes, ecological footprints, and projected land carrying capacity, so that the formed clusters not only reflect existing conditions but also consider the level of vulnerability and potential for ecological strengthening in the future. These classifications are summarized in Table 7, which presents the district groupings and their corresponding development directions, providing a structured basis for tailoring agricultural sector strategies across different ecological conditions.

Table 7. Cluster Grouping of Agricultural Sector Development Directions

Cluster	Districts	Development Directions
Agribusiness	Jombang, and Plandaan	The development direction is focused on developing the local economy to increase economic value, product processing results, and distribution of harvests.
Agroforestry	Wonosalam	The development direction is focused on the utilization of forestry land which can increase the area of conservation land and increase the value of biocapacity, as well as increase the amount of agricultural sector production.
Agroindustry	Ngoro	The development direction is focused on harvest results that are processed into products that provide economic added value through the industrial sector, this is because in Ngoro District there is a plan for an industrial area that can be integrated with the agricultural sector.

Cluster	Districts	Development Directions
Agricultural Cultivation	Bandar Kedung Mulyo, Perak, Gudo, Diwek, Ngoro, Mojowarno, Bareng, Mojoagung, Sumobito, Jogoroto, Peterongan, Megaluh, Tembelang, Kesamben, Kudu, Ngusikan, Ploso, Kabuh	Development directions focus on land protection, land expansion, and increased production. This is because the agricultural sector's performance can still be improved by considering existing conditions. Furthermore, the provision of supporting infrastructure is essential for improving the agricultural sector.

The imbalance in ecological capacity between districts has direct consequences for the direction of Jombang Regency's spatial planning policy. Projected findings indicate that if current land conversion patterns are not controlled, districts that play a strategic role in food production could potentially experience a sharper decline in ecological capacity in the future. This situation is a critical concern in the evaluation of the Regional Spatial Plan (RTRW), given that some of the districts projected to experience deficits are areas with rapid residential and industrial growth. Without strict spatial use controls, this development pressure could exacerbate the decline in land carrying capacity and threaten the sustainability of the regional food production system. Therefore, spatial planning policy needs to be directed towards ensuring the preservation of productive agricultural areas through more comprehensive spatial protection, particularly in districts that have demonstrated significant ecological pressure.

In the context of spatial protection, the implementation of Sustainable Food Crop Land (LP2B) is a key instrument that should be able to reduce the rate of agricultural land conversion. However, field conditions indicate that LP2B implementation in Jombang Regency has not been optimal due to weak legal aspects and the continued lack of synchronization between LP2B policies and regional development priorities. The emergence of districts with projected carrying capacity deficits is evidence that, without a strong legal basis, the protection of productive land is difficult to achieve consistently. Therefore, districts facing land conversion pressures require a more stringent implementation of LP2B, including the establishment of agricultural land protection zones that cannot be easily converted. In addition to LP2B, the Protected Rice Fields (LSD) policy established by the central government also requires attention in its implementation at the regional level. LSD serves not only as a tool to control land conversion but also as an indicator of areas that have a strategic function for food security. However, the effectiveness of LSD depends heavily on its integration with the Spatial Plan (RTRW) and alignment with development investment plans. If the determination of development zones does not consider LSD areas, then the areas that should be supporting food production are at risk of being converted massively in the medium term.

Beyond the aspect of spatial protection, the projection findings also have important implications for agricultural economic development strategies. Variations in ecological capacity between districts have the potential to create unequal contributions to Jombang's agricultural production structure, which in the long term could weaken regional food security. Therefore, a development approach is needed that focuses not only on increasing production but also on agricultural innovation, providing adequate production infrastructure, access to modern agricultural technology, and diversifying commodities based on local potential. Development strategies such as agro-industry, agroforestry, and strengthening supply chains can serve as mechanisms to increase added value while maintaining ecosystem stability. Thus, the agricultural sector in Jombang Regency is expected to remain a pillar of regional food security without sacrificing the sustainability of ecological resources for future generations.

4 Conclusion

This study evaluates the development of the agricultural sector in Jombang Regency through an ecological footprint approach to understand the balance between ecological capacity and agricultural demand. The results show a decline in biocapacity from 2022 to 2024 due to land conversion, declining soil productivity, and increasing development pressure, while projections up to 2044 indicate a potential ecological deficit in several districts, particularly Bandar Kedung Mulyo and Mojowarno. These findings highlight the urgent need to control land conversion, strengthen agricultural land protection, increase land productivity, and integrate ecological indicators into spatial planning to maintain sustainable agricultural capacity. Overall, this study provides a scientific basis for guiding future agricultural development and ensuring long-term food security in Jombang Regency.

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