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Ecological Footprint and Carbon Footprint Analysis to Assess the Sustainability of the Barong Tongkok Region Spatially

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Abstract

Background: Barong Tongkok Subdistrict, West Kutai Regency, East Kalimantan, is experiencing increasing ecological pressure driven by population concentration, land-use change, and rising resource consumption, raising concerns about the region's environmental carrying capacity and long-term sustainability.
Objective: This study aims to assess regional sustainability in Barong Tongkok Subdistrict using a spatially explicit approach that integrates the Ecological Footprint (EF), Carbon Footprint (CF), and Biocapacity (BC).
Method: A quantitative approach was applied using household consumption surveys, land-cover data, emission factors, and Geographic Information Systems (GIS). The EF was calculated based on food consumption, resource use, and built-up land. The CF was estimated from household electricity consumption, LPG use, transportation fuel, and waste burning. BC was derived from land-cover-based productivity using yield and equivalence factors. Sustainability was evaluated through a Sustainability Index (SI), defined as the ratio between BC and the combined EF and CF.
Result: The results indicate significant spatial variation in sustainability across villages. Geleo Baru Village exhibits the highest SI value (31.57), reflecting a strong ecological surplus supported by extensive natural land cover and low population pressure. Conversely, Rejo Basuki Village records the lowest SI value (0.023), indicating a severe ecological deficit due to limited land availability and intensive residential land use. Peripheral villages tend to show ecological surplus, while densely populated areas exceed local carrying capacity.
Conclusion: The integration of EF, CF, and BC within a GIS framework effectively reveals spatial sustainability patterns, providing valuable insights for evidence-based regional planning and targeted strategies to improve local sustainability.

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INTRODUCTION

Regional development that is not accompanied by adequate environmental management can generate significant ecological pressure (Jia et al., 2018). Population growth, expanding economic activities, and land-use change are widely recognized as major drivers of increasing resource consumption and environmental degradation, particularly in developing region

(Borucke et al., 2013). When these pressures exceed the environment's capacity to regenerate resources and absorb waste, ecological deficits emerge, threatening long-term sustainability.

In recent years, the Ecological Footprint (EF) has been widely applied to quantify human demand on ecosystems by measuring the biologically productive land and water area required to support consumption and absorb waste (Fatemi et al., 2021). Although EF has been criticized for policy ambiguity when used in isolation, it remains a powerful diagnostic indicator when combined with complementary approaches (Van den Bergh & Grazi, 2014). Scholars increasingly emphasize that ecological pressure must be assessed alongside consumption-based environmental accounting, which captures indirect and spatially displaced impacts of human activities (Tukker et al., 2020; Wiedmann et al., 2020).

Beyond material consumption, carbon emissions represent a central dimension of ecological pressure. Recent studies demonstrate that humanity's environmental footprint continues to exceed planetary limits, driven largely by energy use, urbanization, and consumption-intensive lifestyles (Hickel et al., 2021; Hoekstra & Wiedmann, 2014). As urban areas expand, land-use change further reduces ecological capacity while amplifying carbon emissions, reinforcing sustainability challenges at regional and local scales (Seto et al., 2012). These dynamics highlight the importance of integrating Ecological Footprint and Carbon Footprint indicators within sustainability assessments.

On the supply side, biocapacity reflects the ecosystem's ability to provide biological resources and absorb emissions. Comparative studies at national and regional levels reveal substantial inequalities between ecological demand and available biocapacity, with some regions maintaining ecological surpluses while others experience severe deficits (Galli et al., 2020). At the global scale, this imbalance has been framed within the broader concept of planetary boundaries, which defines the safe operating space for human development (Rockström et al., 2023; Steffen et al., 2018). Research on sustainable well-being further emphasizes that meeting human needs within ecological limits requires aligning development pathways with environmental capacity rather than continuous material growth (Creutzig et al., 2022; O'Neill et al., 2018).

Despite these advances, most EF and sustainability studies remain concentrated at global, national, or provincial scales, limiting their usefulness for local planning and policy implementation (Newig & Rose, 2020). Empirical evidence shows that ecological pressure and capacity can vary significantly within the same region, particularly at the village or community level, where land-use decisions and consumption patterns are directly shaped (Grossman, 2015; Kopper et al., 2020). Village-scale assessments are therefore essential to reveal localized ecological trade-offs that are often obscured by aggregated analyses.

In Indonesia, rapid development and spatial transformation have intensified pressures on local ecosystems, especially in regions experiencing population concentration and land-use conversion. West Kutai Regency, East Kalimantan, exemplifies this condition, with Barong Tongkok District functioning as an administrative and service center that attracts concentrated human activity. However, spatially explicit information on how ecological demand, carbon emissions, and environmental capacity interact at the village level remains limited (Long et al., 2021).

Based on this gap, the research problem addressed in this study is the lack of village-level, spatially explicit sustainability assessments that integrate ecological demand and environmental capacity within a single analytical framework. This study therefore aims to assess regional sustainability in Barong Tongkok District through the integration of Ecological Footprint, Carbon Footprint, and Biocapacity indicators using a GIS-based approach. The central research question guiding this study is: How do spatial variations in ecological footprint, carbon footprint, and biocapacity determine sustainability conditions across villages in Barong Tongkok District.

METHOD

This research is a descriptive quantitative research article that aims to assess the level of ecological sustainability in the Barong Tongkok District, West Kutai Regency. This approach is used to measure environmental pressures due to human activities and the environment's ability to provide resources and absorb waste through the integration of Ecological Footprint (EF), Carbon Footprint (CF), and Biocapacity (BC) indicators (Borucke et al., 2013).

The research was conducted in Barong Tongkok District, which consists of 21 villages serving as the spatial units of analysis. The population of this study comprised all households within the district. Primary data were collected through a household consumption survey. The sample size was determined to ensure representativeness across villages while considering data availability and field constraints. Households were proportionally selected from each village to reflect differences in population size and settlement characteristics. This approach ensured that variations in consumption patterns across villages were adequately captured.

A stratified random sampling technique was applied. Each village constituted a stratum, and households within each stratum were selected randomly. Stratification was used to reduce sampling bias and to ensure that both densely populated villages and sparsely populated villages were proportionally represented. This technique is appropriate for spatial sustainability analysis, as it captures heterogeneity in household consumption patterns across administrative units.

The data used consists of primary and secondary data. Primary data were obtained through a household consumption survey, covering food consumption, electricity use, LPG, transportation fuel, and waste management practices. Secondary data include population, land cover, administrative boundaries, emission factors, yield factors, and equivalence factors, sourced from the Central Bureau of Statistics, the Global Footprint Network, and the IPCC.

Several validation steps were applied to ensure data reliability and consistency. First, survey questionnaires were checked for completeness and logical consistency before analysis. Second, extreme or implausible values (outliers) in household consumption data were cross-checked against average consumption ranges reported by official statistics. Third, secondary spatial data were validated through cross-referencing land-cover classifications with recent satellite imagery and official spatial planning documents. Finally, all conversion factors, emission factors, yield factors, and equivalence factors used in the calculations followed standardized values published by the Global Footprint Network and the IPCC to ensure methodological consistency and comparability.

Ecological Footprints Calculation

The Ecological Footprint is calculated to measure the need for biologically productive land due to human resource consumption. The EF calculation refers to the Global Footprint Network method with the following formula (Wackernagel & Rees, 1998):

$$EF = \sum \left(\frac{P_i \times C_i}{Y_i} \times EQF_i \right) \quad (1)$$

Information:

P_i : Consumption of resource i (tons, m^3, GJ, etc.)

C_i: Conversion coefficient to gha

Y_i: Global average productivity for product i

EQF_i: Equivalence factor (eg: cropland = 2.52)

Carbon Footprint Calculation

The Carbon Footprint is calculated based on carbon emissions from energy consumption and human activities, including household electricity, LPG use, transportation fuels, and waste incineration. Carbon emissions are calculated using the IPCC emission factors with the following formula (IPCC, 2006):

$$CF_{\text{total}} = \left(E \times EF_{\text{electricity}}\right) + \left(J \times EF_{\text{transportation}}\right) + \left(V \times EF_{\text{LPG}}\right) + \left(M \times EF_{\text{waste}}\right) \quad (2)$$

$$CF_{\text{gha}} = CF_{\text{total}} \times \frac{EQF_{\text{carbon}}}{YF_{\text{carbon}}} \quad (3)$$

Or if using the global average,

$$CF_{\text{gha}} = CF_{\text{total}} \times 0{,}29 \quad (4)$$

Information:
V: LPG volume (kg)
EF: Equivalence Factor of each source
J: Transportation Distance (km)
CF_{total}: Total Carbon Emissions (kg CO_2 eq)
EQF_{carbon}: Equivalence factor for forests (eg: 1.26)
YF_{carbon}: Yield factor of forest land or Global Forest carbon sequestration productivity (gha/ton CO_2), typically around 0.29 gha/ton

Biocapacity Calculation
Biocapacity Ecological Footprint
Based on the Global Footprint Network and Borucke (2013), biocapacity, specifically to calculate the carrying capacity with ecological functions in the ecological footprint, the following equation can be used:

$$BC\ EF = \sum(A_i \times YF_i \times EQF_i) \quad (5)$$

Information:
A_i: Area of each type of productive land (ha)
YF_i: Yield Factor: local vs global productivity ratio
EQF_i: Equivalence Factor
Biocapacity Carbon Footprint
To calculate biocapacity for carbon footprint according to IPCC (2019), the following formula is used:

$$BC\ CF = \sum(A_j \times S_j) \quad (6)$$

A_j: Area of carbon absorbing land cover (ha)
S_j: Carbon uptake coefficient (gha/ha)
Sustainability Index Calculation
The level of regional sustainability is determined using the Sustainability Index (SI), which is the ratio between biocapacity and total ecological pressure derived from EF and CF. The SI formula is stated as follows:

$$SI = \frac{BC}{EF+CF} \quad (7)$$

Information:
SI: Sustainability Index
BC: Total regional biocapacity (gha)
EF: Total ecological footprint (gha)
CF: Carbon footprint in the form of gha (carbon land)
Interpretation of index values:
SI > 1: Sustainable condition (ecological surplus)
SI = 1: Balanced condition (at the limit of sustainability)
SI < 1: Unsustainable condition (ecological deficit)

RESULTS AND DISCUSSION

RESULT

Carbon Footprint and Ecological Footprint Calculation

The results of the Carbon Footprint (CF) and Ecological Footprint (EF) calculations show significant differences among villages in Barong Tongkok District. The CF value is primarily influenced by household energy consumption, which includes electricity, LPG, transportation fuel, and waste incineration. Villages with high population densities and intensive economic activity tend to have higher CF values than villages with rural characteristics. This finding aligns with the Qafleshi (2025), which states that fossil-based energy consumption is a major contributor to carbon emissions in residential areas.

Meanwhile, the EF value is influenced by food consumption, utilisation of natural products, and the area of built-up land. Villages that function as centres of administrative and residential activity exhibit relatively high EF values due to the high resource requirements to support population activities. Conversely, villages with smaller populations and a greater dependence on local resources exhibit lower EF values. This pattern suggests that ecological pressure is determined not only by population size but also by the intensity and patterns of community consumption.

Biocapacity Calculation

Biocapacity (BC) calculations show that the environment's ability to provide resources and absorb emissions is significantly influenced by the area and composition of land cover. Villages dominated by forest and agricultural land cover exhibit high BC values, reflecting a significant ecological capacity to provide food and biomass resources while absorbing carbon emissions. Geleo Baru Village, for example, has the highest BC value, supported by its relatively large area and predominance of natural land cover, thus having a better ability to balance the ecological and carbon pressures generated by human activities.

Conversely, villages with limited land area and predominantly built-up areas exhibit low BC values. This condition indicates a reduced capacity of the local ecosystem not only to support the population's resource needs but also to absorb carbon emissions from energy consumption and transportation activities. Consequently, carbon footprint pressure tends to be greater than the region's carbon absorption capacity. This finding is consistent with the concept of biocapacity proposed by Fu (2020), which states that the conversion of natural land into built-up areas directly reduces a region's ecological capacity and carbon absorption capacity.

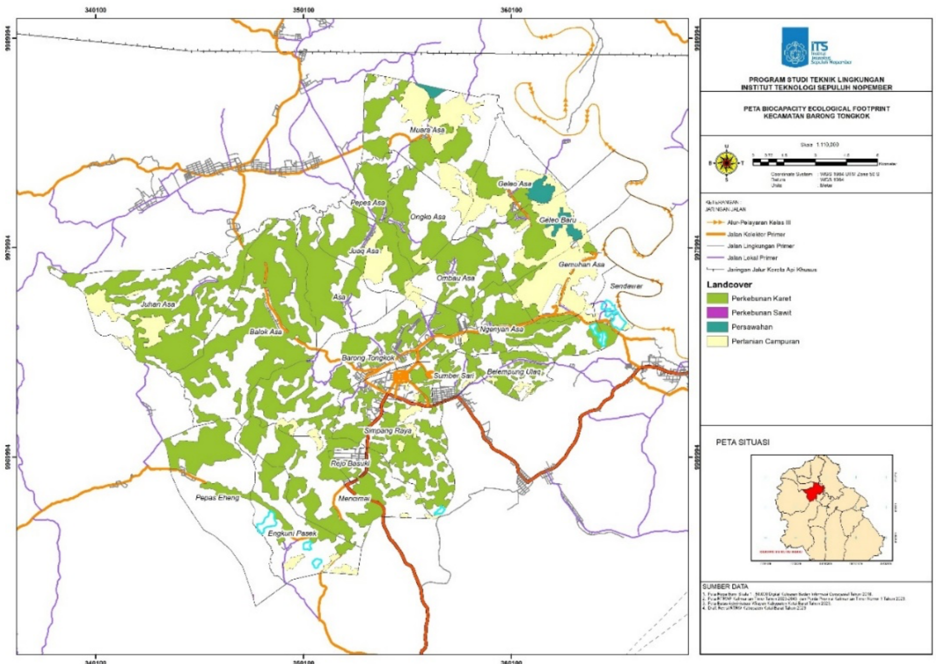

Figure 1 Ecological Footprint Land Cover Map

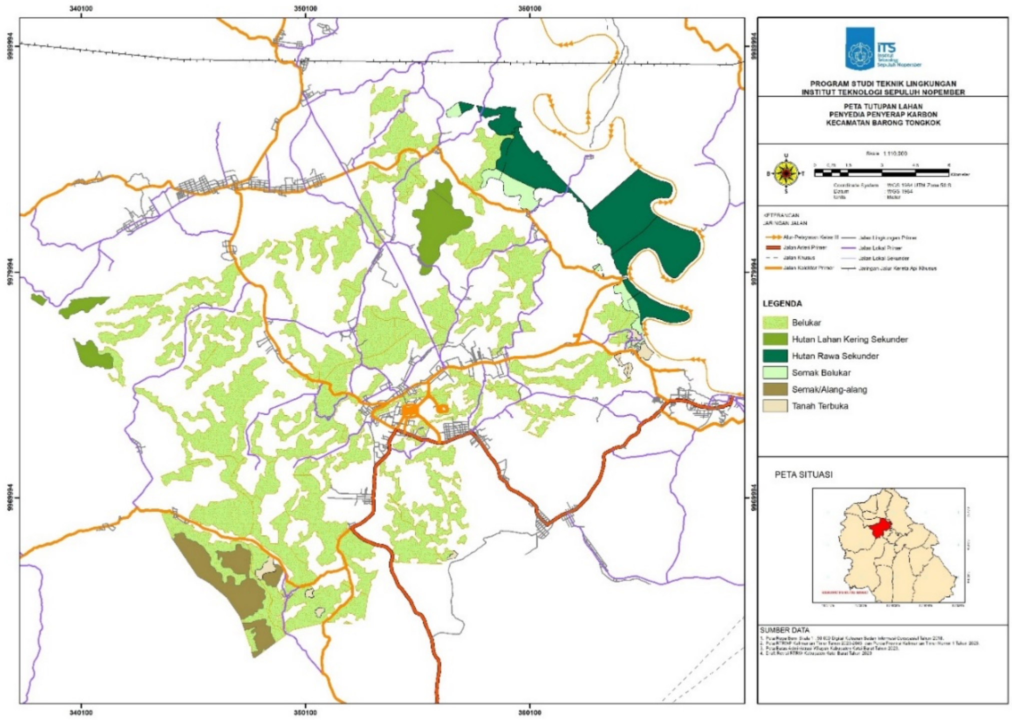

Figure 2 Carbon Footprint Land Cover Map

The land cover map used in the analysis of biocapacity, ecological footprint (EF), and carbon components shows variations in area representing different ecological functions in Barong Tongkok District. Based on the results of spatial data processing, the area of land cover capable of absorbing carbon emissions was recorded at 15,207 ha, while the area of land cover used in the ecological footprint calculation reached 17,181 ha.

The extent of carbon land cover does not represent the size of the carbon footprint but rather describes the area of land with carbon absorption capacity, such as forests, shrubs, and other permanent vegetation. This land cover acts as a carbon uptake area, a crucial component in determining biocapacity, particularly in balancing carbon emissions resulting from human activities. Meanwhile, the ecological footprint covers a broader spectrum of land use, including agricultural land, residential areas, and built-up areas, which are used to meet people's needs for food consumption, energy, and living space.

The difference in area between land cover that absorbs carbon emissions and land cover that provides ecological functions indicates that not all areas utilised for human activities have an ecological function as a carbon sink. This condition emphasises the importance of the existence and protection of natural land cover as a biocapacity buffer, especially in maintaining the balance between carbon emissions produced and the environment's ability to absorb them. This finding also strengthens the role of land cover in determining the condition of ecological surplus or deficit as reflected in the Sustainability Index value.

Sustainability Index Calculation

The integration of EF, CF, and BC yields a Sustainability Index (SI) value that describes the ecological sustainability of each village. The analysis results show a stark contrast in SI variations. Geleo Baru Village has the highest SI value of 31.57, indicating a highly sustainable condition with a large ecological surplus. This value indicates that the village's environmental capacity far exceeds the ecological pressures generated by human activities. Conversely, Rejo Basuki Village has the lowest SI value of 0.023, reflecting an unsustainable condition with a high ecological deficit. The low SI value in this village is caused by a combination of a very limited BC value and high EF and CF pressures due to the dominance of residential areas and the intensity of human activities. In general, outlying villages tend to have SI values greater than one, indicating an ecological surplus, while villages with high population densities show SI values below one.

These results confirm that the balance between ecological pressures and environmental capacity is largely determined by land-use structures and human activity patterns. Therefore, a Sustainability Index-based approach can be an effective tool for identifying priority areas for sustainable development planning and managing environmental pressures at the sub-district level. The following table presents the results of the Sustainability Index (SI) calculation at the village level in Barong Tongkok District, obtained from the integration of the Ecological Footprint (EF), Carbon Footprint (CF), and Biocapacity (BC) values. The SI value is calculated as a ratio between the biocapacity of the area and the total ecological pressure generated by human activities, represented by EF and CF. This index is used to describe the ecological sustainability conditions of each village, whether in the categories of ecological surplus, balance, or ecological deficit.

Table 1. Results of Sustainability Index (SI) Calculations Based on Ecological Footprint, Carbon Footprint, and Biocapacity

No.	Village/Sub-district Name	Biocapacity (BC) (gha)	EF+CF value (gha)	Sustainability Index (SI)	Ecological Conditions	Information
1	Simpang Raya	2,041	2,010	1.01	Balanced	Environmental capacity is balanced with human needs
2	Engkuni Paseq	20,880	2,893	7,217	Sustainable	Environmental capacity exceeds human needs
3	Ongko Asa	9,564	2,812	3.40	Sustainable	Environmental capacity exceeds human needs
4	Ngenyan Asa	18,590	0.848	21.81	Sustainable	Environmental capacity exceeds human needs
5	Geleo Asa	34,500	2,600	13.26	Sustainable	Environmental capacity exceeds human needs
6	Sumber Sari	0.582	1,759	0.33	Unsustainable	Human needs exceed environmental capacity
7	Gemuhan Asa	3,552	2,606	1.36	Balanced	Environmental capacity is balanced with human needs
8	Ombau Asa	5,379	2,330	2.31	Sustainable	Environmental capacity exceeds human needs
9	Juhan Asa	47,693	1,754	27.19	Sustainable	Environmental capacity exceeds human needs
10	Sendawar	8,818	2,437	3.62	Sustainable	Environmental capacity exceeds human needs
11	Balok Asa	14,392	2,241	6.42	Sustainable	Environmental capacity exceeds human needs
12	Asa	11,113	2,325	4.78	Sustainable	Environmental capacity exceeds human needs
13	Muara Asa	30,954	2,011	15.39	Sustainable	Environmental capacity exceeds

No.	Village/Sub-district Name	Biocapacity (BC) (gha)	EF+CF value (gha)	Sustainability Index (SI)	Ecological Conditions	Information
						human needs
14	Mencimai	16,800	1,925	8.73	Sustainable	Environmental capacity exceeds human needs
15	Belempung Ulaq	2,973	1,472	2.02	Sustainable	Environmental capacity exceeds human needs
16	Barong Tongkok	2,041	1,970	1.02	Balanced	Environmental capacity is balanced with human needs
17	Pepas Eheng	15,242	1,720	8.86	Sustainable	Environmental capacity exceeds human needs
18	Juaq Asa	8,721	1,660	5.20	Sustainable	Environmental capacity exceeds human needs
19	Pepas Asa	33,990	2,370	14.32	Sustainable	Environmental capacity exceeds human needs
20	Rejo Basuki	0.035	1,483	0.02	Unsustainable	Human needs exceed environmental capacity
21	Geleo Baru	51,500	1,631	31.57	Sustainable	Environmental capacity exceeds human needs

Based on the results of the biocapacity (BC), ecological footprint and carbon footprint (EF+CF), and sustainability index (SI) calculations, most villages in Barong Tongkok District are in a sustainable condition. Of the total 21 villages/*kelurahan*, 17 villages showed SI values > 1, which indicates that environmental capacity is still able to meet or even exceed human needs. This condition is mainly supported by the relatively large area and the dominance of natural and agricultural land cover that contribute significantly to biocapacity.

Three villages—Simpang Raya, Ngenyan Asa, and Barong Tongkok—are in the balanced category (SI ≈ 1), indicating that resource utilization has approached the limits of environmental carrying capacity. These areas require careful management to prevent them from shifting toward unsustainable conditions.

In contrast, Sumber Sari and Rejo Basuki are in an unsustainable condition, with SI values of 0.33 and 0.02, respectively. The low SI values in these two villages reflect limited biocapacity due to the limited area and the dominance of built-up land, while human consumption and production activities produce relatively high carbon emissions. This condition indicates unsustainability, where human needs have exceeded local environmental capacity.

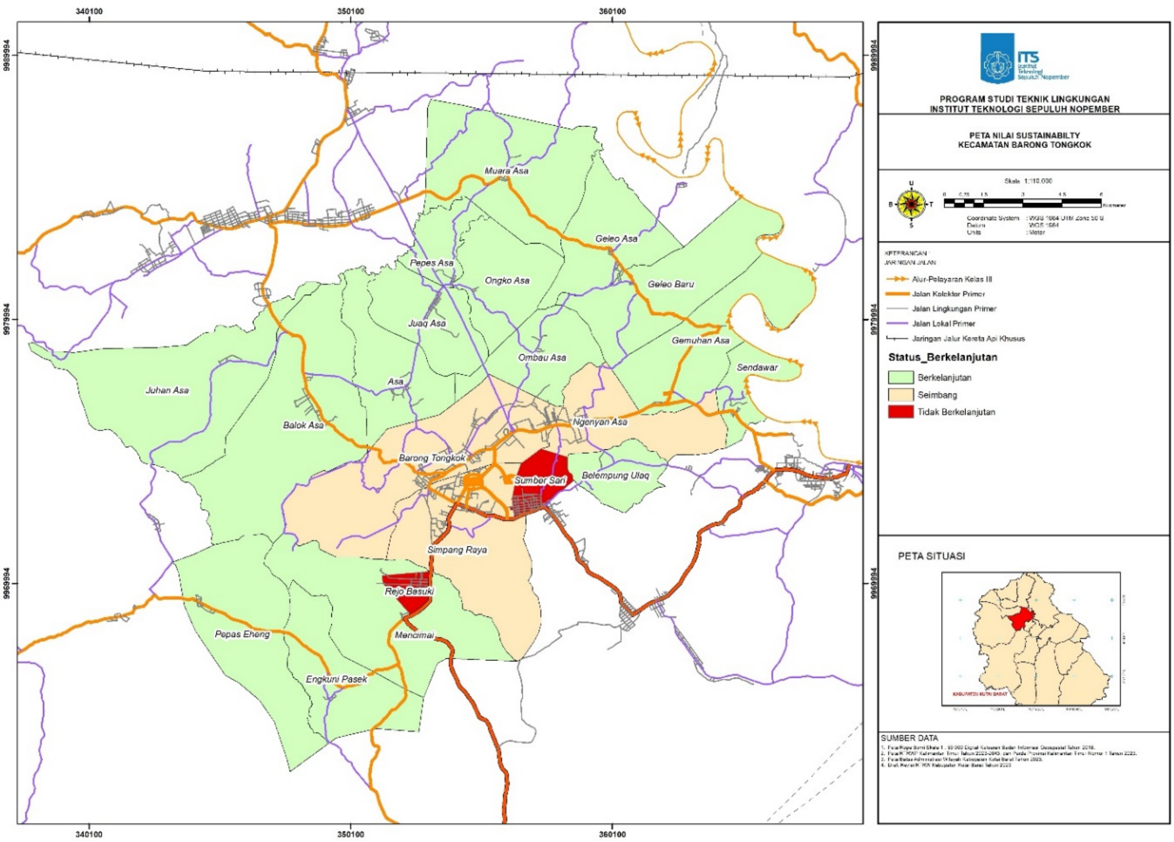

Figure 3. Barong Tongkok District

The ecological sustainability map of Barong Tongkok District shows a contrasting spatial pattern between the central and peripheral areas. Villages located on the outskirts of the district are predominantly in the sustainable category, characterized by relatively large land areas and a predominance of natural and agricultural land cover, resulting in high biocapacity. This condition allows the local environment to meet and exceed consumption needs and the carbon pressure generated by human activities.

In contrast, areas in the district center, particularly the villages of Sumber Sari and Rejo Basuki, exhibit unsustainable conditions due to the high concentration of residential activity, limited land area, and the dominance of built-up land, which reduces the environment's capacity to absorb emissions and provide resources. Several villages near the activity center, such as Barong Tongkok and Simpang Raya, are in the balanced category, indicating that resource utilization has approached the limits of environmental carrying capacity. Overall, this map confirms that the intensity of spatial use and land cover composition are the main factors that shape the level of spatial ecological sustainability in Barong Tongkok District, so that a region-based planning approach is crucial to prevent the expansion of unsustainable conditions.

Discussion

The results of this study indicate that sustainability conditions in Barong Tongkok District are highly uneven across villages and are strongly influenced by the interaction between land-use structure, population pressure, and local biocapacity. The Sustainability Index (SI) values demonstrate that villages with extensive natural and agricultural land cover generally maintain ecological surpluses, while villages dominated by built-up areas tend to experience ecological deficits. This pattern confirms that spatial configuration and land availability play a decisive role in shaping sustainability outcomes at the village level.

From the authors' analysis, the exceptionally high SI value observed in Geleo Baru Village reflects not only low ecological pressure but, more importantly, the presence of substantial biocapacity supported by forest and productive land cover. In contrast, the very low SI value recorded in Rejo Basuki Village highlights a critical imbalance between ecological demand and environmental capacity. This imbalance is primarily driven by limited land area and intensive residential use, which constrain the ecosystem's ability to regenerate resources and absorb carbon emissions. These findings reinforce the authors' argument that sustainability challenges in the study area are less about absolute consumption levels and more about the mismatch between human activities and local environmental capacity.

The spatial analysis further reveals a clear center–periphery pattern, where peripheral villages tend to experience ecological surplus, while villages closer to the administrative and population center exceed their carrying capacity. This finding aligns with broader sustainability research that emphasizes the ecological consequences of urban concentration and land-use intensification (Hoekstra & Wiedmann, 2014; Seto et al., 2012). However, the present study extends these insights by demonstrating that such patterns are already evident at the sub-district and village scale, underscoring the importance of localized sustainability assessments.

In interpreting these results, the authors emphasize that the integration of Ecological Footprint (EF), Carbon Footprint (CF), and Biocapacity (BC) provides a more balanced representation of sustainability than the use of single indicators. While EF and CF capture different dimensions of ecological pressure, biocapacity reflects the actual ecological limits within which human activities operate. This integrated approach supports previous arguments that sustainability assessment should explicitly link environmental demand and supply to avoid partial or misleading conclusions (Galli et al., 2020; Van den Bergh & Grazi, 2014).

The findings also carry important implications for regional planning and environmental management. From the authors' perspective, villages identified as unsustainable or approaching ecological limits should become priority areas for development control, particularly through land-use regulation, protection of remaining green spaces, and promotion of energy-efficient practices. Conversely, villages with high biocapacity and ecological surplus should be safeguarded to maintain their role as ecological buffers. Such differentiated policy responses are consistent with calls for demand-side and spatially targeted sustainability strategies, but this study demonstrates how these strategies can be operationalized at the village level (Creutzig et al., 2022; Hickel et al., 2021).

The discussion highlights that sustainability in Barong Tongkok District is fundamentally a spatial issue. The authors argue that managing land use and aligning development intensity with local biocapacity are essential steps toward maintaining ecological balance. By providing village-level evidence, this study contributes to a more actionable understanding of sustainability that can inform spatial planning and evidence-based policymaking in similar regional contexts.

CONCLUSION

This study demonstrates that sustainability conditions in Barong Tongkok District vary substantially across villages and are shaped by the interaction between human consumption patterns, carbon emissions, and local biocapacity. The integration of Ecological Footprint (EF), Carbon Footprint (CF), and Biocapacity (BC) within a Geographic Information System (GIS) framework enables a spatially explicit assessment of sustainability at the sub-district level. The results show that most villages are in a sustainable condition, with Sustainability Index (SI) values greater than one, indicating that environmental capacity is generally sufficient to support current human activities.

Villages dominated by natural and agricultural land cover and larger land areas tend to exhibit higher biocapacity and stronger sustainability performance. In contrast, villages such as Sumber Sari and Rejo Basuki, which are characterized by limited land area and a high proportion of built-up land, experience unsustainable conditions where ecological demand exceeds environmental capacity. These findings underscore the importance of land-use management and the regulation of human activity intensity as key strategies for maintaining regional sustainability. The results therefore provide a scientific basis for spatial planning and the formulation of environmentally grounded and evidence-based development policies.

Despite these contributions, this study has several limitations. The analysis relies on household survey data and secondary land-cover information, which may involve reporting bias and temporal inconsistencies. Moreover, the use of standardized emission, yield, and equivalence factors may not fully capture local ecological variability. Future research should incorporate longitudinal data, higher-resolution spatial datasets, and locally calibrated coefficients, and should expand the analysis to include socioeconomic and institutional factors influencing sustainability dynamics.

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AUTHOR CONTRIBUTION STATEMENT

Andrew Gilberd Fredrik Mulu contributed to the conceptualization of the study, data collection, GIS processing, quantitative analysis of Ecological Footprint (EF), Carbon Footprint (CF), and Biocapacity (BC), as well as the preparation of the original manuscript draft. Joni Hermana contributed to the research design, provided methodological guidance and supervision, and conducted critical revisions of the manuscript. Arie Dipareza contributed to data validation, spatial and statistical analysis, and refinement of the manuscript. Abdu Fadli Assomadi contributed to methodological validation, overall supervision, substantive review of the manuscript, and final approval of the version to be published. All authors have read and approved the final manuscript.

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