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CAP ON OIL PALM ACREAGE IN INDONESIA BASED ON ENVIRONMENTAL CARRYING CAPACITY FOR DECARBONISATION STRATEGIES

CSIS Indonesia

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Centre for Strategic and International Studies

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Abstract

Indonesia's transition toward biofuel benefits the green economy but also brings challenges, as expanding palm oil production risks deforestation and higher emissions. This study estimates required oil palm plantation area and its carbon emissions to meet physiological needs of the population and biofuel targets by 2030, by integrating scenario planning based on Enhanced Nationally Determined Contribution (ENDC) targets, assessing environmental carrying capacity through an ecological footprint approach, land suitability analysis with Support Vector Machine (SVM), and calculates carbon emissions. Results show that to meet physiological needs and biofuel targets while maintaining ecological balance, oil palm plantations should be capped at 17.67 million hectares, which is lower than the current 18.22 million hectares. Emission reductions are achievable under mitigation scenarios aligned with the ENDC. The findings call for shifting policies from expansion to sustainable intensification and better land governance to support biofuel development without harming the environment.

Keywords: Cap, Carrying capacity, Decarbonisation, Ecological footprint, Oil palm plantation

Table of Contents

Introduction

Energy production and consumption are crucial for the economic growth of all countries (Darrian et al., 2023; Komarova et al., 2022). Currently, fossil fuels dominate the final energy consumption in Indonesia (Bimanatya and Widodo, 2018). However, since fossil energy sources are non-renewable, their availability is declining (Ngarayana et al., 2021). It is anticipated that future growth in the energy sector will lead to a transition towards renewable energy, where Indonesia aims to achieve a 44% renewable energy share by 2030 as part of the Just Energy Transition Partnership (JETP) investment plan (IEEFA, 2024). This transition can help mitigate greenhouse gas emissions, minimise the impact of extreme weather and climate, and ensure a reliable, timely, and cost-effective energy supply (Kabeyi & Olanrewaju, 2022; Kılkış et al., 2022; Umeh et al., 2024).

As a large country with abundant natural resources, Indonesia has experienced an increased demand for renewable energy in line with rising consumption (Erdiwansyah et al., 2021; Langer et al., 2021). Biodiesel, one of the common types of biofuel, is often considered carbon neutral because the carbon dioxide (CO_2) released during its combustion is offset by the CO_2 absorbed by the plants used to produce it (Srivastava et al., 2021). Plants such as soybeans, palm oil, and canola absorb CO_2 from the atmosphere as they grow, which helps to balance out the emissions produced when biofuel is burned (Yan, 2016).

The Indonesian government has been increasing biofuel use to enhance the national energy mix and reduce reliance on fuel imports. Since 2008, Indonesia has started to blend 1-1.5% biofuel (B1-B1.5) for transportation, industry, and power plants. Later, the mandate was increased to B10 for public transport in 2014, B20 in 2016, and B30 in 2020 (Saputra et al., 2021). Finally, in 2023, the government mandated the implementation of B35 in response to global uncertainty about crude oil prices (Wirawan et al., 2024).

In 2022, Indonesia introduced the ambition plan to achieve net zero emissions by 2060 in the Enhanced Nationally Determined Contribution (ENDC), as part of its Second NDC (SNDC), aligned with the Long-Term Low Carbon and Climate Resilience Strategy (LTS-LCCR) 2050. In the energy sector, biofuel production targets include 400,000 KL Fatty Acid Methyl Ester (FAME) in B10 under the Business-As-Usual (BAU) scenario, 18 million KL FAME in B40 under unconditional reduction (CM1), and further enhanced renewable energy (RE) utilisation with international support (CM2) (Ministry of Environment and Forestry, 2022). The optimism continues with the government prioritising the B50 biofuel program targeted for 2029, along with accelerating decarbonisation to meet net-zero goals as part of their green economy agenda. Palm oil will remain the primary feedstock for biofuel production.

Indonesia is currently the world's largest producer and consumer of biofuel, relying on palm oil as the primary raw material due to its competitiveness over crops like cassava, sugarcane, or jatropha. By 2023, Indonesia's biofuel needs will be fully met by palm oil (Putri et al., 2024). Global demand for palm oil is increasing by 4% annually (Sawit Watch, 2021). Although Indonesia holds large palm oil reserves (4-5 million tons) (Saputra et al., 2021), expanding the biofuel industry poses environmental risks, including deforestation, forest fires, and degradation of environmental services, if more land is cleared to expand palm oil plantations (Amalia et al., 2019). To address these concerns, it is essential to quantify the land required for biofuel production while balancing environmental sustainability and economic growth. Biofuel development must not compromise Indonesia's forest conservation and climate resilience efforts.

However, it is suggested that there is a lack of discussion about energy planning in the Indonesian policy environment (Rahman et al., 2021). Existing literature on biofuel policy in Indonesia has primarily focused on statistical analysis of land expansion and deforestation from palm oil demand forecasting (Halimatussadiah et al., 2021; Satya Bumi et al., 2024). For instance, studies have highlighted the potential for significant deforestation driven by increased palm oil cultivation to meet biofuel demands (da Conceição et al., 2021). A study by Gaveau et al. (2022) revealed that over 19 years, Indonesia's forest area declined by 11% (9.79 million hectares), with 32% of this loss (approximately 3.09 million hectares) ultimately converted into oil palm plantations, but not necessary to meet biofuel demand. The research also found that industrial plantations were responsible for replacing more forest areas than smallholder plantings (2.13 million hectares versus 0.72 million hectares). Zhao et al. (2024) and (Pirker et al., 2016) have assessed and mapped areas globally suitable for sustainable oil palm plantations and the limitations to future expansion, including in Indonesia. While their studies account for biophysical and environmental factors and restrictions, they do not consider future demands for physiological needs of population and national biofuel targets. While these analyses provide valuable insights into environmental impacts, a significant gap exists in developing comprehensive methodologies to accurately estimate the land area needed for oil palm plantations to achieve biofuel targets. Addressing this gap is crucial for formulating sustainable biofuel policies that align with Indonesia's ENDC targets.

This research aims to evaluate biofuel policies' impact on the environmental carrying capacity by calculating the palm oil land area requirement and its carbon emission estimation. We use a multi-step approach that integrates scenario planning based on ENDC targets with assessments of environmental carrying capacity. This assessment employs an Ecological Footprint (EF) Calculator and Support Vector Machine (SVM) modelling techniques, as demonstrated in prior studies (Safitri et al., 2021, 2020). This research is crucial to Indonesia's decarbonisation efforts and commitment to ENDC targets, aiming to reduce GHG emissions by 31.89% independently or 43.20% with international support by 2030. Palm oil-derived biofuel is key to achieving these goals, but expansion risks environmental degradation and social conflicts. By assessing how biofuel policies affect environmental quality, the findings will offer concrete data to support the implementation of green energy strategies while safeguarding the environment, thereby helping to align national energy policy with global climate action commitments.

Materials and Methods

2.1. Data

Preliminary data analysis for this study involved data collection, analysis, stakeholder engagement, and synthesis of results. We have identified that the upper limit (cap) for oil palm plantation coverage in Indonesia, based on the Environmental Carrying Capacity, is approximately 18.14 million hectares. However, the previous assessment did not consider the biofuel targets projected by the ENDC. It only considered physiological needs, while specific demands for biofuels have not been accommodated. Although biofuel can also come from other crops, the assumption applied in this research is that the source of biofuel is solely from oil palm.

Based on previous research (Safitri et al., 2021, 2020), there are three groups of data used in this modelling: statistical data to calculate demand in the ecological footprint calculator (non-spatial data), physical parameter data to determine land suitability (spatial data), and constraint variable data to identify areas that cannot be used for oil palm plantations (spatial data). Additional data related to biofuel policies, emission factors, energy mix, and land cover conversion are also required for further consideration.

Statistical data to calculate demand in the ecological footprint calculator includes several sectors of human physiological needs: food, clothing/textiles, infrastructure and timber (housing and public spaces), energy, and specifically related to palm oil demand, as well as carbon emission calculations. In detail, each sector of demand utilises various types of data (Table 1).

***Table 1**. Statistical data of each demand sector (non-spatial)*

Sector Needs	Data Sources
Food	Food Security Statistics Data 2020 and 2022 Ministry of Agriculture (MoA), 2023*; Food Security Statistics Data 2014 MoA, 2015*; Universitas Negeri Yogyakarta
Clothing/Textiles	National Plantation Statistics 2021-2023*
Infrastructure and timber (housing and public spaces)	Decree of the Minister of Settlement and Regional Infrastructure 403/KPTS/M/2002*; SNI 03-1733-2004*; Ecological footprinting literature developed by the University of Michigan (2003) and from the Working Guidebook to the National Footprint Accounts by the Global Footprint Network (Lin et al., 2017) and calculation results (2018)*
Energy	National Electricity Company (PLN) Statistic 2021 and 2022*
Palm Oil	Databoks 2024

Emission	Ministry of National Development Planning, 2014* (Pedoman Teknis Perhitungan Baseline Emisi GRK Sektor Berbasis Energi); UNFCC (National Forest Referencce Emission Level for Deforestation and Forest Degradation)*

**open data*

The food sector includes data on population food consumption, the energy content of food items, a list of food composition, the production volume of each type of food, harvest area for each type of food, footprint intensity for various food types, the area of irrigated and non-irrigated rice fields, fish production, and the area of fishponds. The clothing/textile sector includes data on cotton production volume, cotton harvest area, and cotton production intensity per year. The infrastructure and timber sector (housing and public spaces) includes data on the standard space requirements per person for housing, standard space requirements for public facilities and infrastructure, and footprint intensity data for roundwood. The energy sector includes data on electricity consumption per capita and per customer, as well as the infrastructure for electricity supply provided by the National Electricity Company (PLN). The palm oil sector includes data on the consumption of food, biodiesel, and oleochemicals. Meanwhile, carbon emission calculations are carried out using emission factors for energy use and emission factors for each type of forest.

In this study, a land suitability assessment is conducted, specifically to identify locations suitable for use as oil palm plantations. In the modeling process, land cover and ecoregion data are required, along with 12 physical parameters, as shown in Table 2.

Table 2. *The physical parameters data (spatial)*

Variables	**Data Sourrces**
Land cover	Ministry of Environment and Forestry (MoEF), 2022
Ecoregion	MoEF, 2021
Distribution of oil palm plantations	Sawit Watch, 2024
Rainfall	CHIRRRPS, 2022*
Bulk density	FAO, 2023*
Water availability	Ministry of Public Works (MoPW)
Ground surface temperature	Landsat 8 OLI NASA*
Organic carbon content	FAO, 2023*
Soil pH	FAO, 2023*
Slope	SRTM NASA, 2000*

Elevation	SRTM NASA, 2000*
Total nitrogen content	FAO, 2023*
Terrain ruggedness index	SRTM NASA, 2000*
Topographic wetness index	SRTM NASA, 2000*

**open data*

Meanwhile, constraint variables for oil palm land are applied to limit the land suitability model from allocating oil palm plantations to areas with these constraint variables. The constraint variables used hold significant value for sustaining life, both directly (such as water springs, built-up areas, etc.) and indirectly (such as peatland hydrological units, karst, mangroves, etc.). The function of these constraint variables is to support efforts to protect biodiversity and its habitats from the expansion of oil palm plantations. The data for the constraint variables used are shown in Table 3.

Table 3. *The constraint variables data (spatial)*

Variables	Data Sourrces
Environmental carrying capacity of water supply based on water district	MoPW, 2016
Peatland	MoEF, 2023
Karst	MoA, 2023
Mangrove	MoEF, 2023
Conservation area and protected forest	MoEF, 2023
Primary and secondary forest land cover	MoEF, 2023
Water springs	MoEF, 2023
Slope more than 30%	DEM SRTM NASA, 2000*
Critical land	MoEF, 2023
Protected animals	MoEF, 2023; IUCN, 2023*
Indigenous people	Indigenous Territory Registration Agency, 2024
Key Biodiversity Area (KBA)	Key Biodiversity Area (KBA), 2023
High environmental services for water regulation, habitat & biodiversity, and carbon regulation)	Yayasan Lokahita, 2023
Built-up area	MoEF, 2022

**open data*

To conduct a comprehensive analysis to fulfill these research goals, a robust data collection method is essential. The method in this study relies on quantitative data to build the model, which consist of statistical data dan geospatial data. Statistical data related to palm oil production and consumption from official sources, such as BPS (Central Statistics Agency) or other official agency websites to ensure reliability. Geospatial data uses to conduct the aspect of location, allowing for analysis related to the land requirements for palm oil to meet global goals concerning net zero emissions. In this research, geospatial data was collected secondarily from global databases such as Google Earth Engine or geospatial data that has been previously published internally by us.

2.2. Methodology

The cap of oil palm plantation acreage in Indonesia is determined by considering environmental carrying capacity using an ecological footprint approach for decarbonisation. The plantation area is one of several Land Use/Land Cover (LULC) types that are collectively accounted for in the LULC allocation modelling. In general, there are four stages in this modelling: (1) ecological footprint calculation, (2) planning scenario determination, (3) land suitability analysis, and (4) carbon emission calculation. This modelling is conducted for each island (Sumatera, Jawa, Bali & Nusa Tenggara, Kalimantan, Sulawesi, Maluku, and Papua), so the cap for oil palm plantations in Indonesia is derived from the accumulation of values from each island.

2.3.1 Ecological Footprint Calculation

The ecological footprint is a quantification approach that measures human demand for natural resources in relation to the productive land area required to supply those resources (Wackernagel and Rees, 1996). Since the Earth's surface is finite, the availability of productive land and the amount of resources that can be produced annually are also limited. Therefore, the use of the land area as a unit of measurement for resource provision is chosen to represent the fact that various ecosystem services and ecological resources are provided by the Earth's surface (Wackernagel et al., 2005).

The first step to determine the LULC allocation model is to calculate the land area required to meet basic human needs, such as food, clothing, housing, public space, energy (e.g., biofuel), and other palm oil-related demands. This is done using the EF calculator, which converts these needs into land area requirements.

For each need, scenarios are customised according to research targets, including biofuel policies (e.g., B35, B40). Scenarios include:

- **Less than 100%**: When the region relies on imports.

- **100%**: When the region is fully self-sufficient, with no imports or exports.
- **More than 100%**: When the region produces enough to export to other areas.

By applying these scenarios, the land area required varies, ensuring palm oil demand is balanced with other essential human needs, preventing an egocentric or economically driven approach.

Based on the calculated LULC area requirements, the LULC allocation areas and the calculation of Environmental Carrying Capacity (ECC) are conducted. The LULC allocation is carried out based on the calculated LULC area requirements and the current LULC data. The LULC allocation is performed by adapting the method developed by Lane et al. (2014), with adjustments made to the land allocation rules. Then, the allocated LULC is compared with the LULC requirements per capita to determine the ECC value, which represents the number of people whose needs can be sustainably supported by the ecosystem or land within the study area. The ECC value serves as a benchmark to evaluate whether the scenario aligns with the desired capacity. If not, the process is repeated iteratively to adjust the scenario until the desired ECC value is achieved. The final LULC allocation, with the agreed-upon ECC, is then used to identify specific locations for the allocated areas.

2.3.2 Planning Scenarios

In this study, the scenarios become an input for the Ecological Footprint Calculator. The scenarios follow the NDC framework, including (1) the BAU scenario, which represents a development trajectory without mitigation policies, (2) the Counter Measure-1 (CM1) scenario, which reflects emission reduction efforts through domestic initiatives, and (3) the Counter Measure-2 (CM2) scenario includes additional international support. The scenario will differ for three parameters in the Ecological Footprint Calculator, i.e. fulfilment scenario, consumption, and cropping intensity (Boer et al., 2018).

2.3.3 Land Suitability Analysis

After calculating land allocation from the EF calculation, the most suitable land area for palm oil is determined by integrating the physical land suitability model (by applying the SVM algorithm) and considering the constraint variable described in Table 3.

In the physical land suitability model, land availability and suitability are calculated to determine the supply-side conditions of the land. The SVM algorithm models the land's physical suitability by analysing key physical and environmental variables. The model identifies the most suitable areas for various LULC types, including palm oil plantations.

Following this step, the constraint variables are identified to define environmental and physical constraints that make certain areas unsuitable or unsustainable for palm oil plantations. These constraints restrict the general land suitability analysis by focusing on palm oil characteristics, ensuring that plantations avoid permanent or irreversible environmental damage and direct efforts away from ecologically vulnerable areas.

Finally, the SVM model results are refined by integrating the limiting variables to provide a more reliable assessment of land suitability for palm oil. The model's suitability predictions were compared with existing land cover data. This comparison demonstrated a strong spatial correspondence, indicating that the model effectively captures current land-use patterns and provides a credible basis for land suitability assessment. For instance, if an area is identified as suitable for palm oil but falls within a restricted zone (due to limiting variables), it is recommended that the land retains its existing LULC type. In cases where the land is already used for palm oil plantations, further expansion is discouraged to prevent environmental degradation.

2.3.4 Carbon Emission Calculation

The total carbon emissions for each island are calculated as the sum of carbon emissions from energy use and carbon emissions resulting from changes in land cover allocation. Population energy demand is assessed for electricity and fuel consumption to estimate the forest area required to absorb carbon dioxide (CO_2) emissions from these sources. Then, the carbon emissions from energy use are calculated by multiplying the total energy consumption emissions per capita by the population size. The types of energy consumption considered include electricity use from the energy mix of power plants, natural gas (LPG), fuel for households, and fuel for transportation.

Meanwhile, the carbon emissions from land cover allocation changes are derived by subtracting the existing land cover from the allocated land cover and then multiplying the result by the emission factor of each land cover type. The land cover allocation for each type is obtained through land suitability modelling using SVM, while the existing land cover data is based on 2022. The emission factor is represented as the average carbon stock derived from the sum of above-ground biomass (AGB) and below-ground biomass (BGB) (C tons/ha). This emission factor is adapted from the Rusolono, et al., (2022) in National Forest Reference Level for Deforestation, Forest Degradation, and Enhancement of Forest Carbon Stock by aligning the classification of land cover types used. The emission factors for each land cover type are in the Table 4.

***Table 4**. Emission factor for each land cover type (Rusolono, et al., 2022)*

Land Cover Type	Emission Factor (C ton/ha)
Forest (Non-Protected/Non-Conservation)	214,533
Wetland Agriculture (Rice Fields)	26,290
Dryland Agriculture	100,485
Plantation (Non-Palm Oil)	135,610
Palm Oil Plantation	135,610
Built-Up Area	5,950
Grassland/Shrubland	73,450
Fishpond	0,000
Protected/Conservation Areas	329,617
Water Bodies	0,000

Results

3.1. Cap on Oil Palm Acreage

The scenario analysis results in an oil palm plantation area capped at 17,665,920.51 hectares (17.67 million ha) across all scenarios (BAU, CM1, and CM2) in Indonesia by 2030, ensuring alignment with Indonesia's Nationally Determined Contribution (NDC) commitments and sustainable land-use principles. This cap is not an arbitrary policy decision but rather an outcome of the modelling process, which incorporates environmental carrying capacity assessments, considering not only oil palm plantation needs but other essential land uses. The model also integrates physical land suitability analysis and restricting variables, ensuring that only land meeting agronomic and ecological requirements remains allocated for oil palm cultivation.

Comparing this cap with the existing oil palm plantation area in 2022 (18,215,083.92 hectares or 18.22 million ha) reveals that the current land use exceeds the projected cap across all scenarios. This excess does not directly imply that 549,163.41 hectares must be reduced, but rather that any future oil palm plantation growth must occur within the capped limit, reinforcing the importance of yield intensification and sustainable land management strategies rather than further land expansion. A detailed comparison between the existing oil palm plantation area (2022) and the plantation cap (2030) for each island is presented in Table 5.

Table 5. *Oil palm plantation cap and existing area by island in Indonesia across BAU, CM1, and CM2 scenarios*

Island	Existing Oil Palm Plantation Area in 2022 (ha)	Cap on Oil Palm Plantation Area in 2030 (ha)	Comparison between Existing and Cap
Sumatra	10,704,110.48	10,256,779.89	Existing > Cap
Java	38,612.98	38,612.98	Existing = Cap
Bali & Nusa Tenggara	0.00	0.00	Existing = Cap
Kalimantan	6,682,951.43	6,573,748.26	Existing > Cap
Sulawesi	473,821.01	480,849.94	Existing < Cap
Maluku	24,928.89	25,611.79	Existing < Cap
Papua	290,659.14	290,317.65	Existing > Cap
INDONESIA	**18,215,083.92**	**17,665,920.51**	**Existing > Cap**

Source: modelling results (2025)

The results indicate that Indonesia's existing oil palm area exceeds the projected cap across all scenarios, particularly in Sumatra and Kalimantan, where current oil palm plantations surpass the cap by 447,330.59 hectares and 109,203.17 hectares, respectively. These two regions account for most of Indonesia's oil palm production, and the cap necessitates shifting from expansion-based growth toward productivity-driven intensification strategies to sustain output levels within the designated land constraints.

For Sulawesi and Maluku, the existing oil palm plantation areas remain below their respective caps, with Sulawesi at 473,821.01 hectares in 2022, compared to the capped area of 480,849.94 hectares, and Maluku at 24,928.89 hectares in 2022 against the cap of 25,611.79 hectares. While these islands have remaining allowable space under the cap, this does not imply immediate expansion but rather reflects land suitability assessments that permit potential adjustments within environmental constraints. Similarly, Papua's existing plantation area (290,659.14 hectares) remains just below its cap (290,317.65 hectares), reinforcing its high-conservation-value forest protection measures and limited land-use potential for oil palm. Meanwhile, Java and Bali-Nusa Tenggara remain unchanged, with Java maintaining 38,612.98 hectares and Bali-Nusa Tenggara having no oil palm plantations, reflecting their prioritisation of other land uses such as food production and urban development over oil palm cultivation.

As a result of the modelling process, the same cap is observed across all scenarios (BAU, CM1, and CM2), indicating that the cap for oil palm plantations remains consistent regardless of mitigation strategies. The BAU scenario challenges maintaining production within this cap, as it relies on historical trends without additional mitigation efforts. In contrast, CM1 introduces domestic policies focused on increasing cropping intensity (IP) and yield improvements, while CM2 leverages international support to further enhance sustainability and efficiency. These findings underscore the importance of optimising land productivity to sustain oil palm production while maintaining environmental integrity.

3.2. Oil Palm Plantation Carrying Capacity

Indonesian Law No. 32 of 2009 defines the environmental carrying capacity (ECC) as the ability of the environment to support human life, other living organisms, and their interactions in a balanced manner. In ecological terms, carrying capacity refers to the equilibrium between supply and demand within an ecosystem, where the availability of ecosystem services sets limitations on population growth and human activities that can be maintained without depletion (Rees, 1990).

Regarding oil palm plantations, land use decisions should be a factor in ECC to prevent long-term environmental degradation. As palm oil is in high demand for both local consumption and export, the expansion of this industry must be synchronised with the ecosystem's ability to supply resources and mitigate environmental consequences. Poorly regulated palm oil plantation expansion can result in deforestation, wildfires, biodiversity decline, and increased carbon emissions, ultimately threatening both the environment and human communities.

Modelling Results for Each Scenario

A comprehensive understanding of ECC enables the palm oil industry to function within ecologically and socially sustainable limits. This approach serves as a basis for data-driven policymaking in defining the maximum allowable plantation expansion, curbing unsustainable growth, and enhancing productivity without disrupting ecological balance. By incorporating ECC principles into plantation governance, the industry can contribute to environmental sustainability while advancing national economic objectives and reducing carbon emissions.

An ECC value of less than 100% indicates that the existing population has exceeded the number of people that the environment on that land can support. An ECC value of 100% signifies that the existing population matches the number of people the environment can sustain. Meanwhile, an ECC value greater than 100% implies that the existing population has not yet surpassed the carrying capacity of the environment for that land.

Table 6. *The 2030 oil palm carrying capacity of Indonesia for each scenario*

Region/Scenario	BAU	CM1	CM2
Sumatera	136.23%	132.96%	136.93%
Jawa	1.04%	0.86%	0.86%
Bali Nusa Tenggara	0.00%	0.00%	0.00%
Kalimantan	187.93%	184.48%	184.66%
Sulawesi	56.10%	51.11%	50.65%
Maluku	57.30%	49.16%	49.29%
Papua	133.40%	119.17%	119.86%
Indonesia	**47.97%**	**46.20%**	**46.28%**

Source: modelling results (2025)

Based on the modelling results, the oil palm carrying capacity of Indonesia in 2030 varies across islands and under different scenarios (Table 6). The overall environmental carrying capacity of oil palm plantations in Indonesia in 2030 is calculated based on the total projected population thresholds that can be supported by each island, divided by the projected population of Indonesia in 2030, which is estimated at 292,817,600 people. In the BAU scenario, Indonesia's overall oil palm carrying capacity is projected to be 47.97%. Under the CM1 scenario, the total carrying capacity decreases to 46.20%, reflecting a reduction in the capacity of key regions such as Kalimantan, Sumatra, Papua, and Sulawesi. This decline suggests that implementing mitigation measures leads to a reduction in land availability or productivity for oil palm cultivation. Under the CM2 scenario, the overall carrying capacity sees a slight increase to 46.28%, particularly in Sumatra and Kalimantan, which experience minor improvements compared to CM1.

The significant reduction in capacity under CM1 and CM2 suggests that adopting mitigation measures, such as stricter land-use policies and improved sustainability practices, could effectively limit excessive expansion and reduce environmental degradation. However, the slight improvement in capacity under CM2 may indicate that enhanced mitigation efforts, coupled with sustainable management, can optimise oil palm productivity without drastically reducing land availability.

The modelling results indicate that oil palm expansion in Indonesia remains highly concentrated in Kalimantan, Sumatra, and Papua, with these regions having the highest carrying capacities under all scenarios. Java consistently exhibits minimal carrying capacity, reinforcing the notion that these regions are not feasible for large-scale oil palm cultivation. Meanwhile, Bali–Nusa Tenggara has zero carrying capacity in all scenarios, as there are no existing oil palm plantations in the region due to unsuitable land conditions for oil palm cultivation. This means the region cannot support any of its own palm oil demand and must rely on imports from other islands with surplus capacity.

Thus, islands with a carrying capacity below 100% should consider importing palm oil from regions with higher capacities, such as Sumatra, Kalimantan, and Papua, to meet their needs efficiently. This strategy would help prevent environmental degradation in areas unsuitable for oil palm cultivation while ensuring a stable supply of palm oil for domestic consumption and economic activities.

3.3. Carbon Emission

Carbon emissions from modelling results in Indonesia are estimated based on two primary sources: (1) land cover changes, which include deforestation and land conversion, and (2) energy use, specifically electricity consumption and transportation fuel use. The findings reveal that Indonesia's total carbon emissions are positive across all scenarios, indicating that the country emits more carbon than it absorbs. Under the BAU scenario, total emissions reach 1.039 billion C tons (see Figure 1). With the implementation of mitigation measures, emissions decrease to 955 million C tons under the Counter Measure-1 (CM1) scenario and 959 million C tons under the Counter Measure-2 (CM2) scenario. This reduction reflects the effectiveness of mitigation strategies, particularly in reducing emissions from energy use. However, regional variations exist, with some areas showing significant reductions while others experience increases in emissions under certain scenarios.

Indonesia's carbon emissions vary significantly across regions and scenarios. Java is the largest emitter, contributing over 70% of total emissions under all scenarios due to its high energy consumption and dense population. Mitigation measures under CM1 and CM2 successfully reduce emissions in most regions. In Java, emissions decreased by 4.6% from BAU to CM2 scenario, reflecting the impact of improved energy efficiency. Sumatra experiences a 28.02% reduction in emissions from BAU to CM2, while Kalimantan sees a 26.4% reduction. However, some regions, such as Sulawesi, show an increase in emissions under CM2 compared to CM1, suggesting that mitigation measures in these areas may need to be reevaluated. Additionally, regions like Maluku, Papua, and Kalimantan contribute relatively low emissions, with Papua being the lowest emitter at 5-7 million C ton. These findings highlight the importance of region-specific mitigation strategies to address varying emission patterns.

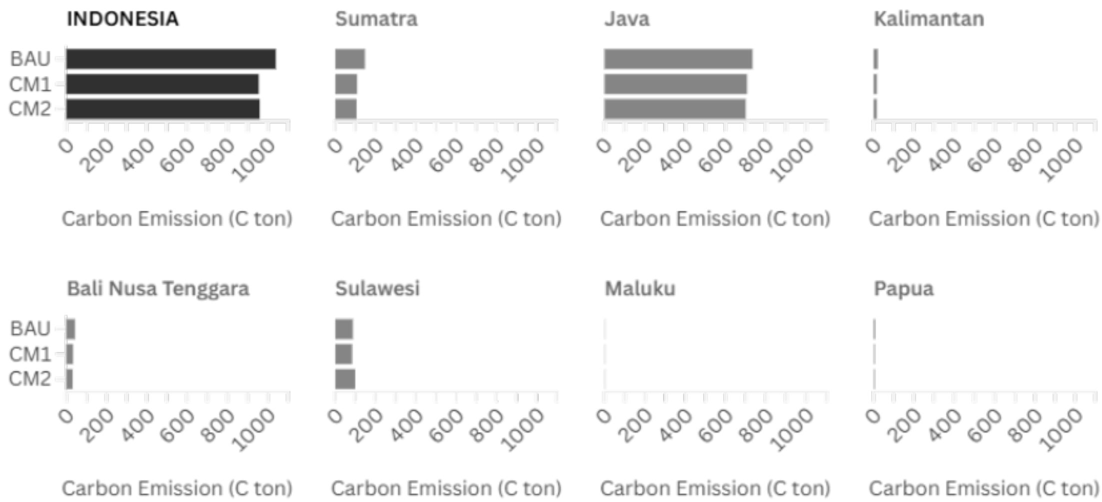

***Figure 1.** Total carbon emission from modelling results (source: modelling results, 2025)*
Carbon Emissions from Land Cover Changes

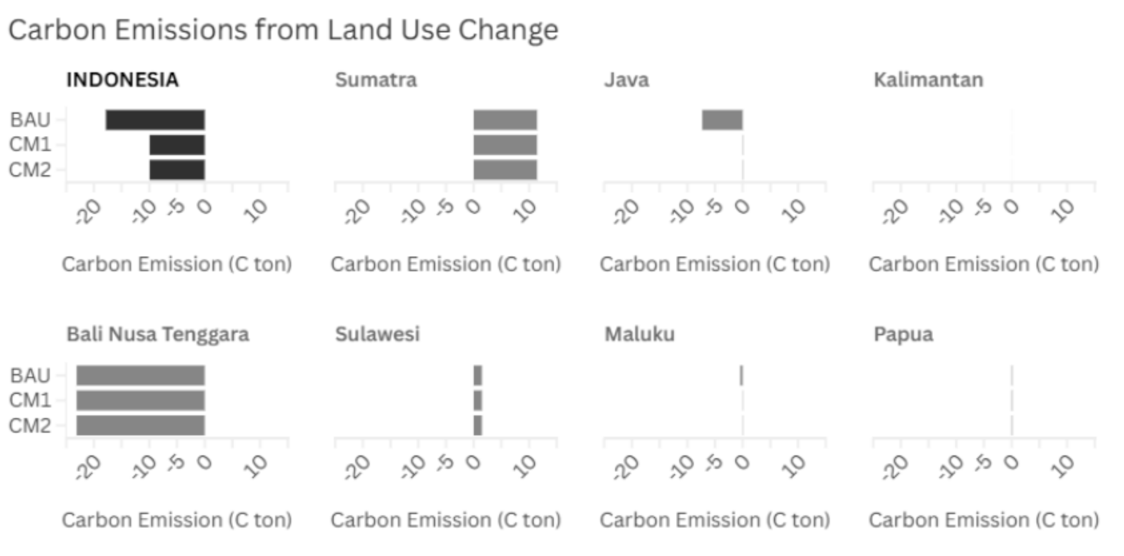

Figure 2. *Carbon emission from land cover changes (source: modelling results, 2025)*

Carbon emissions from land cover changes are estimated based on the difference between existing land cover and allocated land cover under each scenario. The results show that carbon emissions from land cover changes in Indonesia have a negative value, indicating that the land cover change scenario contributes to carbon absorption rather than carbon emissions. For most regions, there is no difference in carbon emissions from land cover changes across the BAU, CM1, and CM2 scenarios. However, Java Island and Maluku Islands show an increase in emissions from BAU to CM1 and CM2 (see Figure 2).

Carbon Emissions from Energy Mixes

In contrast to land cover changes, carbon emissions from energy mixes—specifically electricity consumption and transportation fuel use—are significantly higher, accounting for at least 78% of total emissions. Java is the largest contributor, with emissions of 741 million C ton under BAU, decreasing slightly to 707 million C ton under CM1 and 700 million C ton under CM2 (see Figure 3). Other regions, such as Sumatra and Kalimantan, also show reductions in energy-related emissions, though the total amount of emissions from energy use in these regions is lower compared to Java. However, in Sulawesi, emissions from energy mixes increase under CM2, suggesting that mitigation measures in this region may need to be reevaluated.

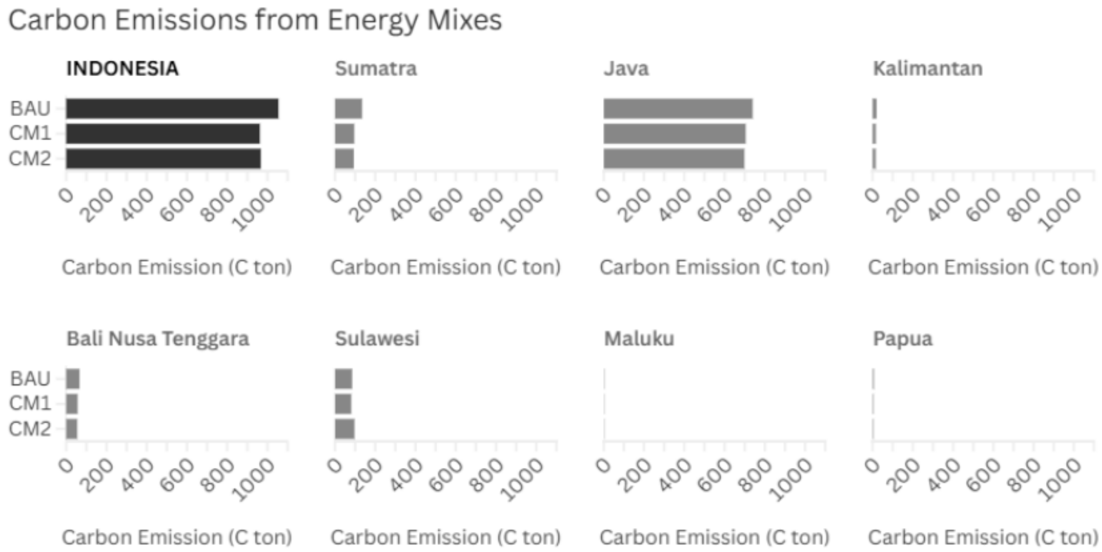

***Figure 3.** Carbon emissions from energy mixes (source: modelling results, 2025)*

3.4. Regional Perspectives of Land Expansion, Carrying Capacity, and Carbon Balance in Sumatra, Kalimantan, and Papua

Sumatra and Kalimantan islands are Indonesia's two largest palm oil-producing regions, contributing significantly to the national and global palm oil supply. Given their extensive oil palm plantation areas, these islands play a central role in economic and environmental considerations related to palm oil production. The cap on oil palm plantation acreage, carrying capacity, and associated carbon emissions were analysed under BAU, CM1, and CM2 scenarios.

The results indicate that the cap on oil palm plantation acreage remains the same across all scenarios for each island. In Sumatra, the plantation area is capped at 10.26 million ha, while in Kalimantan, the cap is 6.6 million ha. This stability across scenarios suggests that further expansion of oil palm plantations is unnecessary, as the current land allocation is considered sufficient under all projected conditions.

The analysis of carrying capacity, which reflects the ability of oil palm plantations to support both the physiological needs of the population and biofuel fulfilment targets, shows that both Sumatra and Kalimantan have a surplus capacity under all scenarios. In Sumatra, the carrying capacity reaches 136.23% in BAU, 132.96% in CM1, and 133.13% in CM2, indicating that existing plantations already exceed the required supply levels. Similarly, Kalimantan exhibits even higher values, with carrying capacities of 184.86% in BAU, 181.47% in CM1, and 181.64% in CM2. These results demonstrate that current palm oil production meets domestic and industrial demand and generates a surplus supply that can be allocated for export, further reinforcing the argument against plantation expansion.

The carbon emissions associated with palm oil production show notable variations across scenarios. In Sumatra, carbon emissions from the energy mix and land cover changes decrease from 146 million C tons in BAU to 108 million C tons in CM1 and 105 million C tons in CM2, indicating that mitigation strategies contribute to lower emissions. Kalimantan exhibits lower emissions overall, with values of 43 million C tons in BAU, 34 million C tons in CM1, and 32 million C tons in CM2. Additionally, in Kalimantan, the change in carbon emissions from land cover shows a negative value across all scenarios, suggesting that the region acts as a net carbon sink rather than a source of emissions. This finding highlights the potential to maintain forested areas and optimise current plantations to support national decarbonisation strategies.

The findings clearly indicate that existing oil palm plantations in Sumatra and Kalimantan are sufficient to meet domestic and international demand without requiring further expansion. The high carrying capacity percentages confirm that Indonesia's current palm oil production exceeds consumption needs and adequately supports biofuel production, with surplus output available for export. However, despite these results, the dynamics of land-use change driven by biofuel policies are now exerting pressure on Papua, home to the country's largest expanse of primary forest and its most significant carbon sink.

In Papua, the analysis reveals that the maximum allowable oil palm plantation area remains constant across all scenarios, capped at 290,317.65 hectares. This stability underscores that further expansion of oil palm plantations is unnecessary, as the current land allocation is adequate to fulfil domestic and biofuel demands under all projected scenarios. Although the plantation area in Papua is smaller than in Sumatra and Kalimantan, the analysis demonstrates that the existing land availability and management in Papua are sufficient to support biofuel policies without additional plantation expansion.

Moreover, the carrying capacity analysis indicates that oil palm plantations in Papua maintain a surplus under all scenarios, with carrying capacities of 133.24% in the BAU scenario, 119.03% in CM1, and 119.71% in CM2. Like Sumatra and Kalimantan, these surpluses suggest that the current oil palm plantations meet domestic biofuel needs and produce excess that can be allocated for export. Further examination reveals that the BAU scenario prioritises production, creating a higher carrying capacity. However, despite efforts to reduce carbon emissions under the CM1 scenario, the carrying capacity remains substantial, albeit slightly lower than in the BAU scenario. Notably, with international support in the CM2 scenario, the carrying capacity of oil palm plantations can still be maintained at a high level. Therefore, the existing plantation areas in Papua are more than adequate to meet consumption requirements, eliminating the necessity for further expansion.

Carbon emissions in Papua from energy mixes and land cover changes decrease across scenarios, from 6,901,730.02 tons of carbon in BAU to 5,194,787.29 C tons in CM1 and 5,127,423.33 C tons in CM2. This reduction in emissions across scenarios demonstrates that mitigation efforts under each scenario can significantly reduce carbon emissions. Additionally, Papua exhibits lower carbon emissions than Kalimantan and Sumatra, underscoring its strategic role in supporting national decarbonisation targets without compromising its forests and conservation areas.

In conclusion, limiting the expansion of oil palm plantations aligns with national decarbonisation efforts. Maintaining the current plantation area while implementing sustainable land management practices can reduce carbon emissions and enhance carbon sequestration, particularly in Papua. Based on these findings, policy efforts should prioritise increasing plantation productivity, adopting sustainable palm oil practices, and optimising energy efficiency rather than expanding plantation areas.

Discussion

As the world's largest producer and consumer of biofuel, Indonesia faces a critical challenge in balancing its renewable energy ambitions with environmental sustainability. In the context of the ENDC, where the government aims to expand biofuel use as part of the national energy mix, ensuring that this transition does not exceed the country's environmental carrying capacity is essential. This study evaluates that balance by modelling three scenarios: BAU, unconditional reduction (CM1), and reduction with international support (CM2), to estimate both the land area required for palm oil production and the potential greenhouse gas (GHG) emissions associated with different land-use pathways. A palm oil cap, therefore, serves not only to assess whether the existing plantations are sufficient to meet the biofuel mix in ENDC targets but also to ensure that pursuing those targets does not lead to increased emissions from land-use change. The cap becomes a critical safeguard to align the two goals of securing biofuel supply and delivering actual CO_2 reductions under Indonesia's climate commitments.

In addition, a palm oil cap is also essential to maintain the global competitiveness of Indonesian palm oil in tightening environmental regulations. Standards such as the Roundtable on Sustainable Palm Oil (RSPO), Indonesia's own ISPO, and the European Union Deforestation Regulation (EUDR) are progressively raising expectations for traceability and sustainability (Econusantara, 2024). The EUDR, expected to be enforced by the end of 2025, will require products to prove that commodities such as palm oil are free from deforestation or forest degradation. Failure to comply with this regulation will result in fines, making Indonesian exports to the EU less competitive and potentially losing market access. By implementing a cap, Indonesia can maintain international market access, while ensuring domestic biofuel demand and reducing emissions to achieve Indonesia's ENDC targets. In addition, currently there is the International Sustainability and Carbon Certification (ISCC) to ensure that agriculture, biofuel, and other materials that relate to land expansion and GHG emission (including palm oil plantation) are sustainable, fully traceable, deforestation-free, and climate-friendly supply chains. The ISCC is relatively new for Indonesia's palm oil realm. If the ISCC is implemented to support environmental regulation, it is necessary to consider the alignment of the ISCC mechanism with Indonesia's current policy.

Discussions on palm oil caps are closely tied to Indonesia's energy security strategy. Biofuel from palm oil significantly reduces dependence on fossil fuels and insulates the domestic energy sector from geopolitical uncertainties. However, the question is whether biofuels in the energy mix can reduce Indonesia's emissions and support Enhanced ENDC targets, besides electrification and renewable energy implementation efforts. Using Life Cycle Analysis (LCA) methods, Jeswani et al. (2020) indicate that biofuels have lower carbon emissions than fossil fuels, even though the emissions from nitrogen oxides (NOx) are still high in the air (Sheehan et al., 1998). For instance, palm oil-based biodiesel may reduce GHG emissions by over 60%, meeting the EU Renewable Energy Directive (RED) mandate (Jeswani et al., 2020). However, this efficiency did not account for emissions related to deforestation.

The expansion of palm oil by converting forests, including peatland, and land (deforestation) to oil palm can cause GHG emissions to occur. Jiwan et al. (2009) mention that even oil palm plants have the potential to sequester carbon. Still, this contribution is insufficient to cover the emissions produced, resulting from land conversion, especially in forests on mineral and peat soils. Aligned with Hassan et al. (2011), which incorporated land use change (LUC) into LCA calculations, it was found that palm oil biodiesel generates GHG emissions up to 3 to 40 times higher than fossil fuels, mainly due to the large-scale land conversion of peatlands and forest deforestation. Importantly, this issue is not unique to palm oil, and other biodiesel products also exhibit higher emissions than fossil fuels when LUC is considered. The result highlights that land expansion for palm plantation in Sumatra and Kalimantan is unnecessary and needs to be restricted because sufficient palm oil is produced from the current production. This restriction potentially pressures land expansion from other islands, such as Papua, as the lowest carbon emitter. The current palm oil production in Papua was reported to be threatening the biodiversity, food sovereignty, and social culture conditions of indigenous people (Laia, 2024; Runtuboi et al., 2021). This evidence strengthens the statement that the efforts to expand oil palm or extensification will only lead to greater deforestation and higher risks. It will even contribute to world climate change and have the effect of losing international confidence in Indonesia's climate commitments, for example, in the NDC framework. For these conditions, oil palm expansion or extensification is not a priority; the most logical thing is to increase the productivity of oil palm plantations or land intensification.

Talking about land intensification, the Government of Indonesia (GOI) currently applies the People's Palm Oil Replanting Program (*Program Peremajaan Sawit Rakyat*/PSR), which aims to boost yields through replanting with high-quality seeds and applying Good Agricultural Practices (GAP) (BPDP, 2025). CELIOS (2024) shows that a moratorium on new palm oil permits, combined with PSR, will yield better long-term economic and environmental outcomes, including higher GDP, tax revenue, and job creation, while it can also increase competitiveness in the international market. However, current average yields in Indonesia fall well below government targets. While the Ministry of Agriculture targets 36 tons/ha/year, most community plantations produce only 2.5–3.4 tons/ha/year. By comparison, Malaysian plantations often yield 4–6 tons/ha/year (Hassan et al., 2011). Approximately 40% of Indonesia's oil palm area is over-aged and needs replanting. Despite PSR's potential, there are several obstacles in the realisation of this program as mention in Redaksi InfoSAWIT (2025), including, 1) Administrative difficulty for farmers to prove that land is free from forest areas; 2) The high price of Fresh Fruit Bunch/FFB makes smallholders maintain their oil palm trees rather than replacing them with new plants because it takes years to return to productivity; and 3) The partnership program between the company and the planters is not optimal. The other obstacles, such as the farmer's reluctance due to the discontinued revenue, the limited incentives, the land tenure governance, the lack of a farmer mentoring program, and the certified palm seed availability (Hutasuhut et al., 2023; Mayarni et al., 2023; Syafira et al., 2024), highlight the need for supporting policy and law enforcement in PSR implementation.

In addition, integration with commodity diversification (including cocoa, coffee, and rubber) and sustainable land management (soil rehabilitation) can be much more beneficial since it can promote alternative crops, reduce palm oil dependency, and encourage agroforestry models for mixed-use cultivation while aligning with the needs of the local community (Azahari et al., 2024; Khasanah et al., 2020). The challenge in realising commodity diversification is determining and regulating certain strategic commodities because they bring more economic value than other commodities (Husin et al., 2023). The Strategic Commodities Bill (RUU Komoditas Strategis), currently being discussed in parliament, provides an opportunity to institutionalise this diversification and become a pillar of Indonesia's food security (Ramdan, 2024). The process includes either monoculture crops diversification (particularly for enhancing palm oil replanting process in large-scale capacity to gain high economic benefit) or agriculture technique diversification (including mosaic landscape with intercropping or agroforestry, particularly for existing palm plantations which are relatively old) to diversify the palm variety so it can fulfil locals daily needs. However, its implementation must be synchronised across ministries to avoid overlap and ensure effective governance.

It can be concluded that in fulfilling biofuel demands for the energy mix while ensuring environmental sustainability, land intensification and commodity diversification should be the ultimate approach in palm plantations. Still, if land extensification is necessary and unavoidable, it must be strictly allocated to land with low carbon emission factors. Without strict land management and law enforcement (such as diversification of monoculture crops, or mosaic landscapes with intercropping or agroforestry), biofuels could undermine Indonesia's ENDC targets rather than help fulfil them. Since different land uses can emit diverse emission impacts, the decision of land extensification should consider comprehensive emission factor data from distinct types of land cover, such as following the National Forest Reference Emission Level for Deforestation and Forest Degradation guideline to limit GHG emission production. It is also essential to align the application of policies with the spatial plan (RTRW) to prevent competing land use interests. A precise map of low-emission land zoning is a critical prerequisite for inclusion in the spatial plan.

Conclusion

This study estimates that by 2030, the cap on oil palm plantation acreage should be set at 17.67 million hectares to balance physiological needs, biofuel targets, and economic growth while maintaining environmental carrying capacity. The results indicate that implementing mitigation measures (CM1 & CM2) can effectively reduce carbon emissions, supporting Indonesia's decarbonisation efforts. However, the existing oil palm plantation area exceeds this cap, with 18.22 million hectares currently cultivated. This excess highlight the need for alternative policy strategies rather than further expansion.

There are at least five alternative policy strategies: productivity over expansion, sustainable land management, commodity diversification, capped growth approach, and stronger land governance. First, instead of expanding plantations, increasing productivity should be the focus. Improving cropping intensity and yield efficiency can enhance output without converting additional land. Sustainable land management is also essential to optimise existing plantations while minimising environmental impact. Best management practices can help maintain soil fertility, reduce emissions, and enhance long-term sustainability.

Diversifying commodities is another crucial approach. Reducing dependency on oil palm by promoting alternative high-value crops can create economic resilience while alleviating pressure on land resources. Moreover, future oil palm development must remain within the allocated land limits to avoid ecological risks and ensure long-term sustainability. Furthermore, stronger land governance is also necessary to prevent illegal expansion and mitigate deforestation risks. Strengthening policy enforcement and monitoring mechanisms can help maintain land use integrity. Finally, shifting policy priorities toward efficient land use, carbon-efficient production, and economic sustainability will be critical in achieving both environmental and economic objectives.

Given that Indonesia's current oil palm plantations surpass the sustainable cap, future policies must emphasise productivity, sustainability, and responsible land use. By implementing these strategies, Indonesia can maintain its leading position in global palm oil production while supporting climate commitments and long-term environmental resilience.

Establising a cap on oil cap plantation acreage is a critical step toward aligning land-use policy with environmental sustainability goals. However, this study also highlights several limitations that should be addressed through future research to ensure that the cap is both scientifically robust and practically enforceable. First, the analysis does not explore the market feasibility or economic incentives for farmer. Without clear financial mechanisms, diversification may remain theoretical rather than practical. Second, this study assumes a relatively stable trajectory of biofuel demand, yet global energy transitions – such as electrification and adoption of alternative fuels- may alter the long-term role of palm oil in energy mix. Future analyses should therefore incorporate alternative biofuel feedstocks and their land-use implications to capture comprehensive future demand and supply. Third, while the proposed cap is a strong policy recommendation, this study does not assess specific enforcement mechanisms. Research on legal frameworks, monitoring technologies, and compliance incentives is critical to ensure that the cap is effectively implemented.

For future research, reforestation or ecological restoration options for land currently planted with oil palm that exceeds the proposed cap should also be explored. Where reforestation is not feasible, conversion to forest-friendly crops (such as agroforestry systems or alternative crops with lower ecological impact) should be prioritised to enhance landscape resilience, ensuring that selected solutions also demonstrate strong economic viability. Additionally, it would be valuable to analyze the level of targeted productivity that can be achieved without necessitating further land expansion. Moreover, improving the accuracy of carbon emission estimates by adopting dynamic modeling approaches, such as integrating satellite-based carbon flux data, should also be considered given the significant variability in land-use change dynamics.

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