



RESEARCH ARTICLE

Integrating FAO-based land suitability evaluation with regional economic analysis to identify flagship agricultural commodities in Lalundu and Bambakaenu transmigration areas, Central Sulawesi, Indonesia

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Abstract

Land suitability studies commonly assess biophysical conditions without incorporating regional economic performance, thereby reducing their relevance to site-specific commodity development planning. This study integrates Food and Agriculture Organization of the United Nations (FAO)-based land suitability evaluation and regional economic analysis to identify flagship agricultural commodities in the Lalundu and Bambakaenu transmigration areas, Donggala Regency, Central Sulawesi, Indonesia. Field surveys, soil sampling and land characterisation were conducted from August to December 2025, across 33313.72 hectares (ha) delineated into 20 land mapping units (LMUs); climatic analysis drew on 10-year records (2015–24). An FAO matching approach classified each LMU for five perennial crops (cocoa, coconut, coffee, durian and oil palm) into four suitability classes: highly suitable (S_1), moderately suitable (S_2), marginally suitable (S_3) and not suitable (N). Location quotient (LQ) and shift-share analysis (SSA) were used to assess regional economic performance using agricultural production data from 2020–24. All five commodities were predominantly classified as S_3 , covering over 92 % of the study area, with water availability, rooting conditions, nutrient availability and retention and erosion risk as the principal limiting factors. Feasible improvement measures increased the potential S_2 area for oil palm and coconut from 362.24 ha (1.09 %) to 8854.51 ha (26.59 %), but did not alter the suitability class for cocoa, durian and coffee unchanged; LMU 6 (2103.51 ha; 6.31 %) remained unsuitable (N) for all crops because of permanent rooting constraints. The LQ and SSA results identified oil palm as the flagship commodity in Lalundu (Rio Pakava Subdistrict), with a five-year average LQ of 3.58 and a net shift of +34.98 %. Cocoa was identified as the flagship commodity in Bambakaenu (Pinembani Subdistrict), with an LQ of 3.20 and the highest net shift among the evaluated commodities (+699.79 %). Assessing biophysical suitability or economic performance in isolation risks commodity misalignment; the integrated framework provides a replicable basis for evidence-based land-use planning in transmigration and other frontier agricultural regions.

Keywords: biophysical constraints; cocoa; Donggala Regency; location quotient; oil palm; shift-share analysis

Introduction

Transmigration areas are strategic zones for agricultural expansion, rural economic development and population relocation in Indonesia, intended to raise land productivity and improve the livelihoods of both migrant and indigenous populations (1, 2). Achieving these objectives requires matching agricultural commodities to the biophysical capacity of the land and the economic structure of the region (3). In the Lalundu and Bambakaenu transmigration areas of Donggala Regency, Central Sulawesi, crop selection has been guided by general development policies and short-term economic considerations rather than by

systematic land evaluation (4). Such practices increase the risk of land degradation, inefficient resource management and unstable production and can create a mismatch between land characteristics and land use.

Soil composition, drainage, topography and hydrology vary widely across transmigration areas and directly influence land productivity and crop adaptability (5, 6). Land suitability evaluation identifies crops best suited to local conditions, reduces the risk of degradation and supports attainable productivity (7, 8). Utilising land beyond its natural capacity leads to degradation with biophysical, social, cultural and economic consequences for local communities

(9). Suitability classes vary according to the intended land use and its management requirements, therefore land-use decisions must satisfy both biophysical and economic criteria to ensure sustainable development (10–12).

Most land suitability studies focus on soil, climate and topography but pay limited attention to regional economic performance (12, 13). They identify physically suitable land but cannot determine whether a crop is compatible with existing production systems, market access, or regional economic benefits. Flagship commodity studies face the opposite problem: they rank commodities according to production share, growth, or comparative advantage using location quotient (LQ) and shift–share analysis (SSA) (14, 15), but neglect land capability and may therefore recommend crops that perform poorly under local conditions. These limitations are particularly evident in transmigration frontier areas. Heterogeneous soils, developing infrastructure and emerging markets make crop selection critical for livelihood outcomes, yet few studies in the international literature integrate biophysical assessment with economic analysis.

A physically suitable crop may contribute little to the local economy, whereas an economically dominant commodity poses sustainability risks when cultivated on land with severe biophysical constraints; neither criterion alone supports sound development decisions. This study integrates Food and Agriculture Organization of the United Nations (FAO)-based land suitability evaluation with the LQ and SSA to identify flagship commodities among five perennial crops (oil palm, cocoa, durian, coconut and coffee) across 20 land mapping units (LMUs) in the Lalundu and Bambakaenu transmigration areas. The integrated framework was expected to identify different flagship commodities from those indicated by economic indicators alone and on predominantly marginal land, to favour commodities combining minimum biophysical feasibility (suitability class S_3 or higher) with strong economic performance (LQ greater than one and a positive net shift) rather than the highest level of land suitability.

Materials and Methods

Study area

The study was conducted in the Lalundu and Bambakaenu transmigration areas, located in the Rio Pakava and Pinembani subdistricts, respectively, of Donggala Regency, Central Sulawesi, Indonesia. The geographical location of the study area is shown in Fig. 1. The area lies between $1^{\circ}08'45''$ and $1^{\circ}27'04''$ S and $119^{\circ}25'44''$ and $119^{\circ}46'35''$ E, covering 33313.72 hectares (ha) with a mean annual rainfall of $1483.2 \text{ mm yr}^{-1}$ and mean monthly rainfall of $123.6 \text{ mm month}^{-1}$. The area falls within the B2 agroclimatic zone, with two dry months (monthly rainfall below 100 mm) and seven wet months (monthly rainfall above 200 mm). Mean monthly air temperature was 26.5°C and mean relative humidity was 84.6 %.

Data collection

Field surveys generated primary data through soil sampling, direct observation of land characteristics and verification of existing land use. Composite soil samples were collected from representative field units within each land mapping unit (LMU) and analysed for crop-relevant soil properties (16). Soil texture was determined using the hydrometer method (17); pH (water (H_2O) and potassium chloride (KCl) was measured potentiometrically (18); organic carbon was determined by the Walkley–Black method (19); total nitrogen by the Kjeldahl method (20); available phosphorus by the Bray I method (21); and exchangeable potassium and cation exchange capacity (CEC) by the ammonium acetate method (22). Slope gradient and drainage conditions were assessed in the field.

Secondary data comprised climatic records, spatial datasets and agricultural production statistics. Climatic variables including air temperature, relative humidity and rainfall were obtained from official meteorological records for 2015–24 and processed as monthly and long-term averages. Soil-type maps were obtained from the Indonesian Center for Agricultural Land Resources Research and Development (Balai Besar Sumber Daya Lahan Pertanian, BBSDLR) (23), land-use maps from the Geospatial Information Agency (Badan Informasi Geospasial, BIG) (24) and

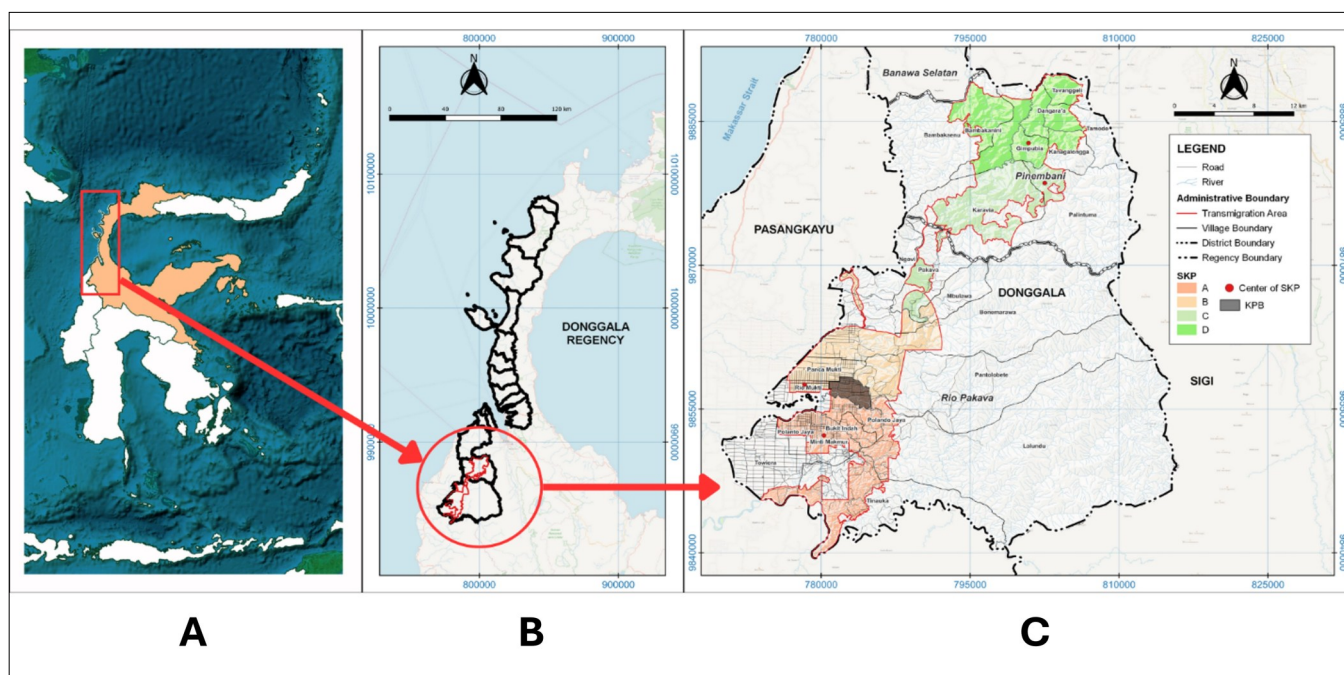


Fig. 1. Geographic location of the study area. A: regional position of Central Sulawesi within Indonesia; B: location of the Lalundu and Bambakaenu transmigration areas within Donggala Regency; C: detailed map of the Lalundu and Bambakaenu transmigration areas in Rio Pakava and Pinembani subdistricts, based on administrative boundary data from BIG (24), Donggala Regency, Central Sulawesi, Indonesia.

slope maps were derived from the National Digital Elevation Model (DEMNAS) (25). These layers were overlaid at a scale of 1:250000 to delineate 20 LMUs, which served as the spatial reference units for soil sampling, field surveys and observations. Agricultural production statistics for 2020–24 were obtained from the Central Statistics Agency (BPS) of Donggala Regency (26) to support the regional economic analysis.

The five commodities (oil palm, cocoa, durian, coconut and coffee) were selected based on their current cultivation status, availability in official production statistics, relevance to local livelihoods and strategic importance for plantation and horticultural development in Donggala Regency.

Land suitability evaluation

A FAO-based matching approach was used to evaluate each land mapping unit against crop-specific requirements for climate, soil and topography. Climatic parameters included rainfall, temperature and relative humidity. Soil and land parameters included drainage (permeability), soil texture, effective soil depth, soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium, CEC and slope gradient.

Land characteristics within each LMU were matched against crop requirement criteria to assign a land suitability class (LSC): highly suitable (S_1), moderately suitable (S_2), marginally suitable (S_3), or not suitable (N), following the FAO framework. Crop requirement criteria and class thresholds for oil palm, cocoa, durian, coconut and coffee are presented in Supplementary Table 1–5 (27). A most-limiting-factor approach was applied, whereby the parameter with the lowest rating determined the overall suitability class for each LMU–crop combination, thereby identifying the dominant biophysical constraints.

Actual suitability was based on existing land characteristics without management intervention. Potential suitability was estimated by assessing the effects of feasible improvement measures on manageable limiting factors including nutrient availability, soil acidity, nutrient retention and erosion risk. Permanent or difficult-to-modify factors including rainfall, relative humidity, soil texture, effective soil depth and slope gradient were considered non-improvable; slope itself cannot be altered, but erosion risk was considered partly manageable through soil and water conservation measures. GIS techniques were used to delineate the LMUs and generate the actual and potential suitability maps, from which the suitable area for each crop was quantified.

Regional economic analysis

The LQ and SSA were used together to identify economically dominant commodities. The LQ measured the relative production concentration of each commodity in the study area against Donggala Regency. Commodities with an $LQ > 1$ were classified as base commodities, indicating a higher production concentration in the study area than the regency average. The LQ was:

$$LQ = \left\{ \frac{x_i}{x_j} \right\} \left\{ \frac{X_i}{X_j} \right\} \quad (\text{Eq. 1})$$

Where LQ is location quotient; x_{ij} and x_{0j} represent the production of commodity i and total agricultural production at the subdistrict level respectively; and X_{ij} and X_{0j} represent the corresponding district-level values.

The SSA decomposed production change into three components: the regional share component (RSC), the proportional shift component (PSC) and the differential shift component (DSC):

$$\text{Shift-Share} = \text{RSC} + \text{PSC} + \text{DSC} \quad (\text{Eqn. 2})$$

$$\text{RSC} = \frac{Y_t}{Y_o} - 1 \quad (\text{Eqn. 3})$$

$$\text{PSC} = \frac{Y_{it}}{Y_{io}} - \frac{Y_t}{Y_o} \quad (\text{Eqn. 4})$$

$$\text{DSC} = \frac{y_{it}}{y_{io}} - \frac{Y_{it}}{Y_{io}} \quad (\text{Eqn. 5})$$

where $y_{(i0)}$ and $y_{(it)}$ represent the production of commodity i in the study area at the beginning and end of the analysis period respectively; $Y_{(i0)}$ and $Y_{(it)}$ represent the corresponding district-level values; and $Y_{(0)}$ and $Y_{(t)}$ represent total district-level production at the beginning and end of the period, respectively. The analysis period was 2020–24. The net shift was the sum of PSC and DSC. Commodities with zero or absent baseline production were excluded from the SSA or interpreted using field survey data because the growth ratio is undefined when the baseline value is zero.

The LQ and SSA were computed for all agricultural commodities recorded in official statistics across the estate, horticulture and livestock sub-sectors and the LQ was expressed as a five-year average. Results for the five perennial crops evaluated for land suitability are reported here to facilitate the integration of biophysical and economic assessments. Durian is classified under the horticulture sub-sector, therefore its regional share base differs from that of the estate crops and its SSA components are not directly comparable.

Integration of land suitability and economic criteria

The integrated framework for flagship commodity identification is shown in Fig. 2. The procedure comprises two parallel components. The biophysical component draws on primary soil and field data, together with secondary spatial and climatic data, to delineate LMUs and conduct the FAO land evaluation, producing actual and potential suitability classes for each commodity. The economic component uses district- and subdistrict-level production data whereby the LQ identifies comparative advantage and the SSA characterises growth dynamics and local competitiveness.

A commodity was designated as a flagship when it met two criteria: a minimum regional suitability class of S_3 or higher, ensuring basic biophysical viability; and economic dominance, indicated by an $LQ > 1$ and a positive net shift. Economic performance was further classified using an LQ–SSA quadrant typology: leading ($LQ > 1$, positive net shift), potential ($LQ > 1$, negative net shift), developing ($LQ < 1$, positive net shift) and backward ($LQ < 1$, negative net shift). Commodities classified as unsuitable (N) were excluded from development planning regardless of their economic performance. The framework identifies commodities that are both biophysically feasible and economically competitive, rather than ranking crops using a single indicator.

Data analysis

Economic indicators were computed using Microsoft Excel (Microsoft 365). Spatial analysis, LMU delineation and suitability and land-use mapping were conducted in ArcGIS 10.8 (Esri, Redlands, CA, USA) using overlay (intersect) and spatial join operations on the soil type, land-use and slope layers. Results are presented as tables, thematic maps and cross-comparisons of biophysical and economic outcomes across subdistricts.

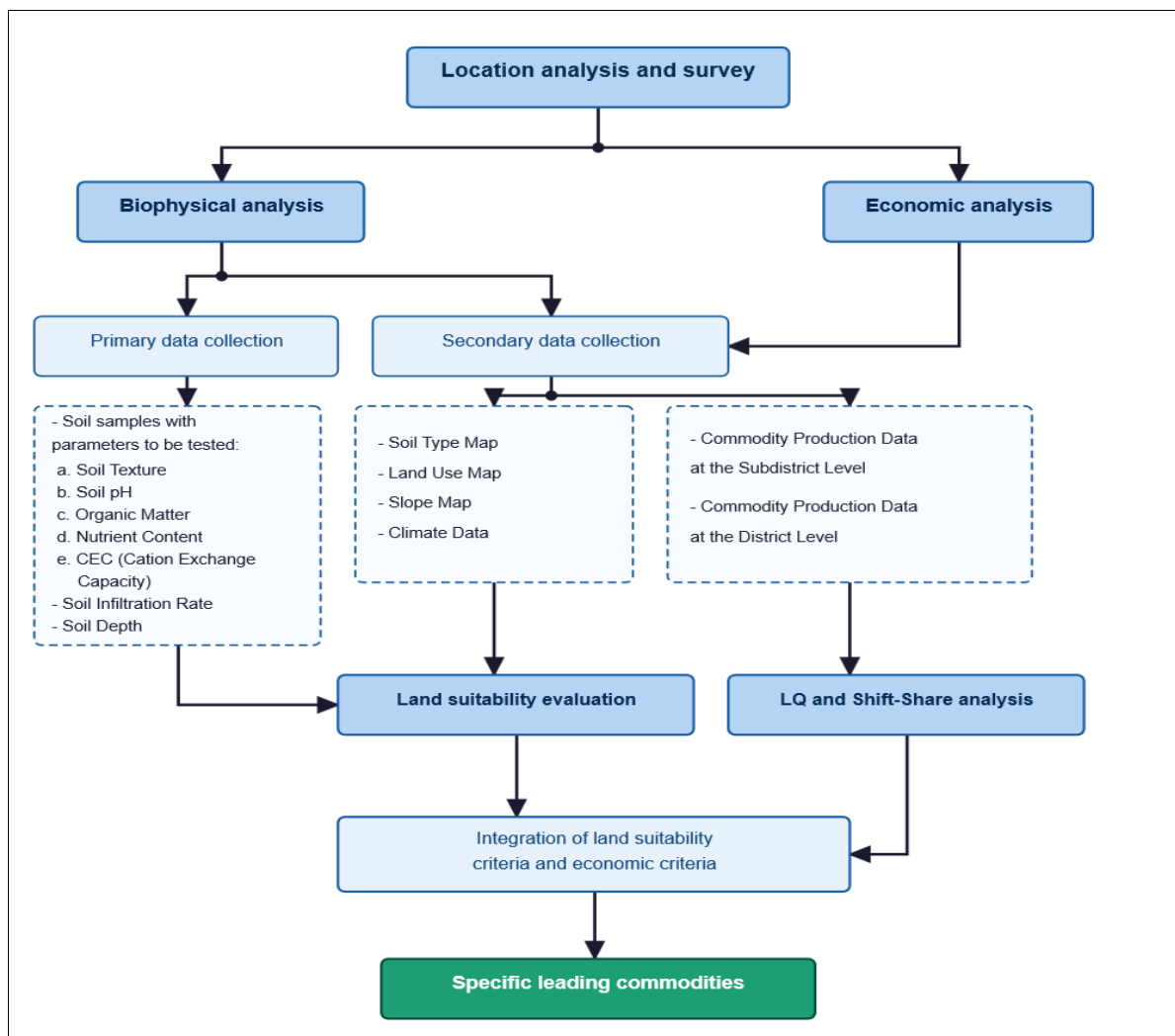


Fig. 2. Integrated framework for flagship-commodity identification combining FAO-based land suitability evaluation and regional economic analysis.

Results and Discussion

Land characteristics and suitability classes

The 20 LMUs encompassed distinct climatic, edaphic and topographic conditions; the thematic input layers and LMU boundaries are shown in Fig. 3. Each LMU was evaluated against the land qualities governing crop performance in the tropics: temperature, water availability, oxygen availability, rooting conditions, nutrient availability, nutrient retention and erosion hazard.

Thermal conditions were favourable (mean temperature 26.5 °C), with ratings of S_1 for oil palm, cocoa, durian and coconut and S_2 for coffee (Table 1). The mean temperature falls within the 24–28 °C optimum range for tropical perennial crops; consequently, thermal stress was not a limiting suitability factor in any LMU (28). Rainfall (1483.2 mm yr⁻¹) was more limiting, with ratings of S_2 for oil palm and coconut and S_3 for cocoa, durian and coffee while relative humidity (84.6 %) imposed marginal to moderate limitations for cocoa and coffee. Cocoa requires 1500–2500 mm yr⁻¹ of rainfall for optimal growth; at 1483.2 mm yr⁻¹, the study area lies just below this threshold. Studies on cocoa production in Indonesia have identified rainfall as the primary driver of productivity and reported that temperature changes of 1 °C have only marginal effects on yield (28, 29), whereas oil palm yield declines under water deficit regardless of thermal conditions (30). Overall water-related factors imposed greater constraints on suitability than temperature across all five commodities.

Actual suitability was predominantly S_3 for all five commodities across most LMUs (Table 2), indicating that cultivation is feasible but limited by several interacting factors. Effective soil depth ranged from 40–79 cm and soil texture from sandy loam to silty clay, consequently, rooting conditions (rc) were the most common constraint, particularly in LMUs with sandy or shallow profiles. Soils were acidic (pH 4.47–6.41), with available phosphorus ranging from 12.08–31.12 mg kg⁻¹ and exchangeable potassium from 9.85–21.92 cmol kg⁻¹. Phosphorus availability limited oil palm and coconut (na) and potassium limited cocoa (nr). The CEC (14.48–23.18 cmol kg⁻¹) was generally adequate and drainage was rarely a dominant constraint. Several LMUs had steep slopes (up to 29 %), increasing the erosion hazard (eh) (31, 32). These constraints are permanent or difficult to modify under the FAO land-evaluation framework.

Land mapping unit 6 was the exception, being rated unsuitable (N) for all five commodities because an effective soil depth of only 40 cm imposed a severe rooting constraint. This unit should be excluded from crop development, irrespective of its economic importance.

Potential suitability improved in a limited number of LMUs but remained constrained overall (Table 3). Oil palm and coconut could attain S_2 in LMUs 1, 5, 16, 19 and 20 through erosion-control measures; oil palm in LMU 16 additionally required phosphorus application, while water availability and rooting conditions, determined by rainfall, soil texture and effective soil depth remained

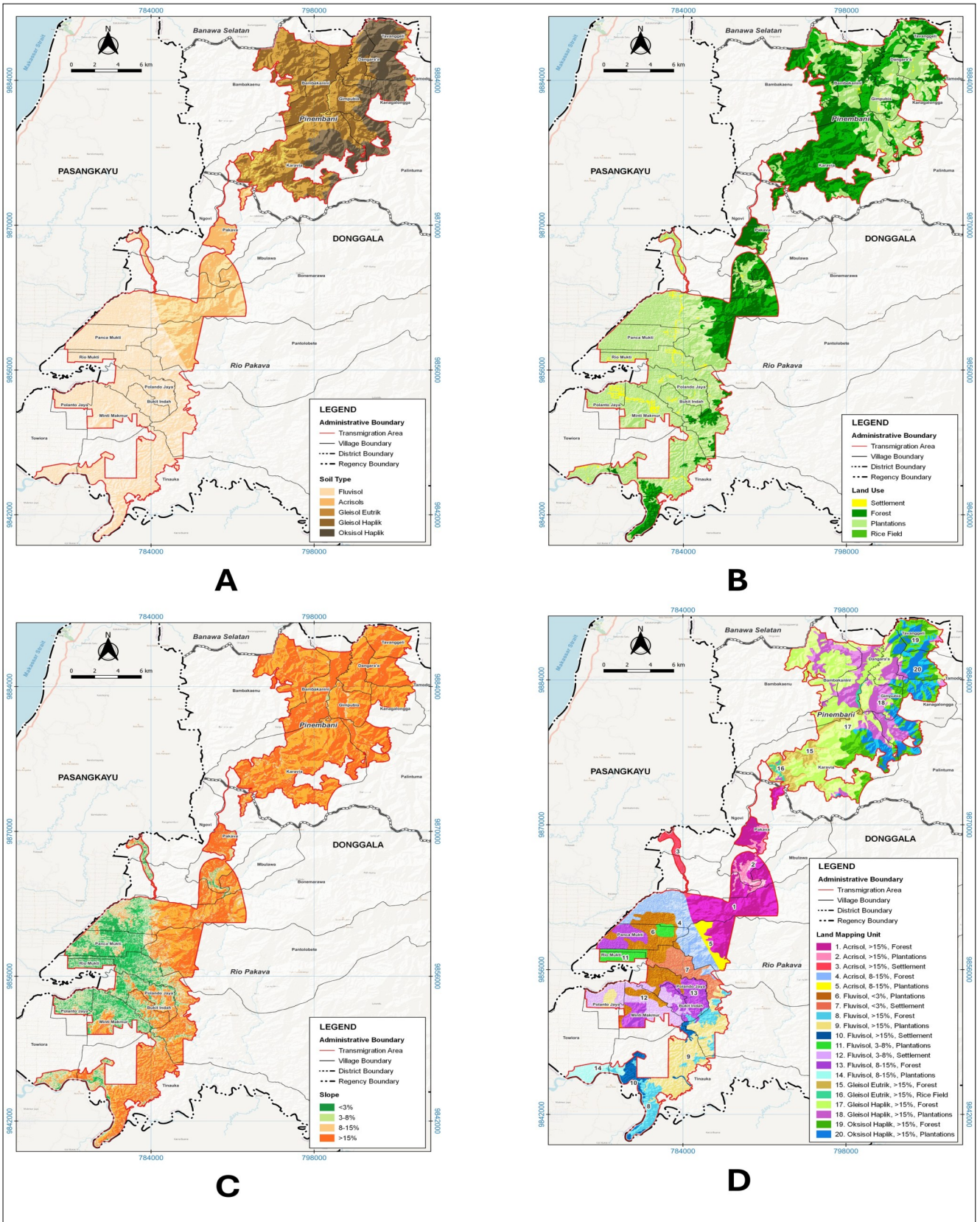


Fig. 3. Thematic maps used for LMU delineation. A: soil type, obtained from BBSDLP (23); B: land use, obtained from BIG (24); C: slope, derived from DEMNAS (25); D: the resulting LMU map.

Table 1. Climatic suitability classes of the evaluated commodities in the study area

Commodity	Temperature (26.5 °C)	Rainfall (1483.2 mm year ⁻¹)	Relative humidity (84.6 %)
Oil palm	S ₁	S ₂	S ₂
Cocoa	S ₁	S ₃	S ₃
Durian	S ₁	S ₃	S ₁
Coconut	S ₁	S ₂	S ₁
Coffee	S ₁	S ₂	S ₂

Table 2. Measured land characteristics and actual land suitability class (with dominant limiting factors) of the 20 land mapping units (LMUs) for the five evaluated commodities

LMU	Drainage (mm h ⁻¹)	Texture	Depth (cm)	N-total (%)	P ₂ O ₅ (mg kg ⁻¹)	K ₂ O (cmol kg ⁻¹)	CEC (cmol kg ⁻¹)	pH (H ₂ O)	C-org (%)	Slope (%)	Oil palm	Cocoa	Durian	Coconut	Coffee
1	377	Silty clay	75	0.10	23.42	20.14	20.55	5.92	0.88	17	S ₃ oa,eh	S ₃ wa,oa,eh	S ₃ wa,oa,eh	S ₃ oa,eh	S ₃ wa,oa,eh
2	912	Silty loam	72	0.19	16.85	13.25	18.61	5.51	1.75	16	S ₃ rc	S ₃ wa,rc	S ₃ wa,rc	S ₃ rc	S ₃ wa,rc,na,eh
3	7610	Sandy loam	68	0.10	13.15	15.35	18.79	5.97	0.55	17	S ₃ oa,rc,eh	S ₃ wa,oa,rc,nr,eh	S ₃ wa,oa,rc,eh	S ₃ oa,rc,eh	S ₃ wa,oa,rc,na,eh
4	350	Silty clay	73	0.09	17.19	10.98	20.36	5.13	0.59	9	S ₃ oa,rc,na	S ₃ wa,oa,na,rc,nr	S ₃ wa,oa,rc,nr,na	S ₃ oa,rc,na	S ₃ wa,oa,rc,na
5	511	Silty clay loam	77	0.10	26.34	21.92	18.21	5.35	0.66	11	S ₃ wa,oa,rc,na,nr,eh	S ₃ wa,nr	S ₃ wa,nr	S ₃ wa,oa,rc,na,nr, eh	S ₃ wa,nr
6	6640	Sandy loam	40	0.10	16.49	19.35	16.97	6.10	0.89	2	Nrc	Nrc	Nrc	Nrc	Nrc
7	2251	Loam	67	0.16	24.06	20.15	21.22	5.49	1.52	2	S ₃ rc	S ₃ wa,rc	S ₃ wa,rc,nr	S ₃ rc	S ₃ wa,rc
8	311	Silty clay	62	0.07	18.50	12.35	20.77	5.52	0.62	18	S ₃ oa,rc,na,eh	S ₃ wa,rc,na,nr,eh	S ₃ wa,oa,rc,na,eh	S ₃ oa,rc,eh	S ₃ wa,oa,rc,nr,na,eh
9	469	Clay loam	65	0.21	21.76	10.25	22.09	4.47	1.67	16	S ₃ oa,rc	S ₃ wa,oa,rc,nr	S ₃ wa,oa,rc,nr	S ₃ oa,rc,nr	S ₃ wa,oa,rc,nr,eh
10	488	Silty loam	72	0.12	12.08	12.45	19.29	5.55	0.70	15	S ₃ oa,rc	S ₃ wa,oa,rc,nr	S ₃ wa,oa,rc	S ₃ oa,rc	S ₃ wa,oa,rc,nr,eh
11	2341	Loam	55	0.05	17.01	16.35	20.02	5.92	0.77	5	S ₃ rc,na	S ₃ wa,rc,na,nr	S ₃ wa,rc,na	S ₃ rc,na	S ₃ wa,rc,nr,na
12	2139	Loam	68	0.09	22.04	21.15	22.05	5.45	0.78	6	S ₃ rc,na	S ₃ wa,rc,na,nr	S ₃ wa,rc,nr,na	S ₃ rc,na	S ₃ wa,rc,nr,na
13	6810	Sandy loam	76	0.08	16.70	9.85	17.30	4.77	0.65	12	S ₃ oa,na	S ₃ wa,oa,na,nr	S ₃ wa,oa,nr,na	S ₃ oa,nr,na	S ₃ wa,oa,nr,na
14	1683	Loam	66	0.17	13.21	13.58	22.30	6.02	1.63	9	S ₃ rc	S ₃ wa,rc	S ₃ wa,rc	S ₃ rc	S ₃ wa,rc
15	1922	Loam	67	0.06	16.23	13.28	19.02	5.24	0.56	24	S ₃ rc,na,eh	S ₃ wa,rc,na,nr,eh	S ₃ wa,rc,nr,na,eh	S ₃ rc,na,eh	S ₃ wa,rc,na,nr,eh
16	2591	Loam	79	0.08	20.59	19.63	20.77	5.82	0.89	28	S ₃ na,eh	S ₃ wa,na,eh	S ₃ wa,na,eh	S ₃ na,eh	S ₃ wa,na,eh
17	2721	Loam	63	0.08	16.25	10.25	19.02	4.77	0.79	27	S ₃ rc,na,eh	S ₃ wa,rc,na,nr,eh	S ₃ wa,rc,nr,na,eh	S ₃ rc,nr,na,eh	S ₃ wa,rc,nr,na,eh
18	7233	Sandy loam	72	0.10	21.60	18.45	14.48	5.52	0.97	29	S ₃ oa,rc,eh	S ₃ wa,oa,rc,eh	S ₃ wa,oa,rc,eh	S ₃ oa,rc,eh	S ₃ wa,oa,rc,eh
19	751	Silty clay loam	75	0.21	31.12	21.15	23.18	6.41	2.29	27	S ₃ eh	S ₃ wa,eh	S ₃ wa,eh	S ₃ eh	S ₃ wa,eh
20	732	Clay loam	76	0.07	24.95	16.35	19.56	5.66	0.70	24	S ₃ na,eh	S ₃ wa,na,nr,eh	S ₃ wa,na,eh	S ₃ na,eh	S ₃ wa,nr,na,eh

Measured land characteristics are crop-independent; the last five columns give actual suitability class and dominant limiting factors for each commodity; Limiting-factor symbols- wa: water availability; oa: oxygen availability; rc: rooting conditions; na: nutrient availability; nr: nutrient retention; eh: erosion hazard; Suitability classes- S₁: highly suitable; S₂: moderately suitable; S₃: marginally suitable; N: not suitable; To find per-parameter suitability ratings (S₁–N) for each characteristic, match measured values against crop-requirement thresholds in Supplementary Table 1–5; the derived ratings appear in Supplementary Table 6–10; P₂O₅: phosphorus pentoxide; K₂O: potassium oxide; CEC: cation exchange capacity; C-org: organic carbon.

Table 3. Potential land suitability classes, dominant limiting factors and feasible improvement measures across land mapping units (LMUs)

LMU	Potential LSC	Dominant limiting factors	Improvement measures
Oil palm			
1, 19, 20	S ₂ wa,rc,eh	Water availability, rooting conditions, erosion hazard	Slope conservation water availability rooting conditions non-improvable
5	S ₂ wa,rc	Water availability, rooting conditions	Non-improvable
16	S ₂ wa,rc,na,eh	Water availability, rooting conditions, P availability, erosion hazard	Phosphorus fertilisation slope conservation
2-4, 7-15, 17, 18	S ₃ rc	Rooting conditions	Non-improvable
6	N rc	Rooting conditions	Non-improvable
Cocoa			
1, 5, 16, 19, 20	S ₃ wa	Water availability	Non-improvable
2-4, 7-15, 17, 18	S ₃ wa,rc	Water availability, rooting conditions	Non-improvable
6	N rc	Rooting conditions	Non-improvable
Durian			
1, 5, 16, 19, 20	S ₃ wa	Water availability	Non-improvable
2-4, 7-15, 17, 18	S ₃ wa,rc	Water availability, rooting conditions	Non-improvable
6	N rc	Rooting conditions	Non-improvable
Coconut			
1, 19, 20	S ₂ wa,rc,eh	Water availability, rooting conditions, erosion hazard	Slope conservation remainder non-improvable
5	S ₂ wa,rc	Water availability, rooting conditions	Non-improvable
16	S ₂ wa,rc,eh	Water availability, rooting conditions, erosion hazard	Slope conservation
2-4, 7-15, 17, 18	S ₃ rc	Rooting conditions	Non-improvable
6	N rc	Rooting conditions	Non-improvable
Coffee			
1, 5, 13, 16, 17, 19, 20	S ₃ wa	Water availability	Non-improvable
2-4, 7-12, 14, 15, 18	S ₃ wa,rc	Water availability, rooting conditions	Non-improvable
6	N rc	Rooting conditions	Non-improvable

Potential LSC values show the suitability class each LMU can reach by addressing manageable limiting factors; permanent constraints are excluded. Factor symbols as in Table 2.

fixed. Cocoa, durian and coffee remained at S₃ because their principal constraints, water availability and rooting conditions, are beyond the scope of ordinary management interventions and improvements in soil fertility alone were insufficient to increase suitability. Land mapping unit 6 remained N. Fertilisation, liming, organic matter addition and erosion measures alleviated some manageable constraints; however, permanent limitations related to water availability and rooting conditions restricted improvements to incremental gains.

Spatial distribution of land suitability

Across both subdistricts, S₃ was the predominant actual suitability class for all five commodities. For oil palm and coconut, S₃ covered 30847.97 ha (92.60 %), S₂ covered 362.24 ha (1.09 %) and N covered 2103.51 ha (6.31 %), as shown in Fig. 4. Cocoa, durian and coffee were classified as S₃ over 31210.21 ha (93.69 %) and N over 2103.51 ha (6.31 %), with no land classified as S₂. This reflects the classification of LMU 5, which was rated S₂ for oil palm and coconut, but S₃ for cocoa, durian and coffee (Table 4). A predominance of S₃ land is not unusual in plantation-crop suitability assessments in Indonesia; comparable FAO-based studies in Central Java and Gorontalo have reported interacting physical and chemical constraints that place the majority of land in the marginal suitability class (33, 34). In the present study, the S₃ classification reflects the realistic conditions for cultivation on tropical frontier soils, rather than an unsuitable production environment.

After the application of feasible management interventions, the S₂ area for oil palm and coconut increased from 362.24 ha (1.09 %) to 8854.51 ha (26.59 %) whereas the S₃ area decreased to 22355.70 ha (67.10 %). In contrast, cocoa, durian and coffee

remained classified as S₃ over 31210.21 ha (93.69 %) (Fig. 5). The 8854.51 ha that could attain S₂ correspond to LMUs where nutrient deficiencies and partly controllable erosion hazards constitute the principal constraints, representing the subset identified by the FAO framework as amenable to improvement through targeted management interventions (27). Targeting phosphorus inputs and erosion-control measures to these specific LMUs, rather than applying interventions uniformly across the landscape, would improve resource-use efficiency and reduce management costs.

Soil depth, rainfall and rooting conditions imposed the principal limitations on land suitability, rather than fertility constraints that can be addressed through management. The persistence of S₃ under both actual and potential suitability scenarios for cocoa, durian and coffee indicates the presence of largely permanent constraints. Unlike nutrient deficiencies, limitations associated with inadequate rainfall and shallow rooting zones cannot be corrected at the farm scale without substantial infrastructure investment which is generally impractical in frontier agricultural settings.

Land mapping unit 6 (2103.51 ha; 6.31 %) was classified as unsuitable for all five commodities. Although it occupies a relatively small area, its identification is important because a crop-development strategy based solely on the dominant suitability class would overlook a unit where cultivation is biophysically unjustified. Land-use studies in Indonesia have identified very shallow soils as a common characteristic of N-class land, which is more appropriately allocated to protection functions than to agricultural production (35). Accordingly, conservation, protective vegetation, or other low-impact land uses represent the most suitable management options for this unit.

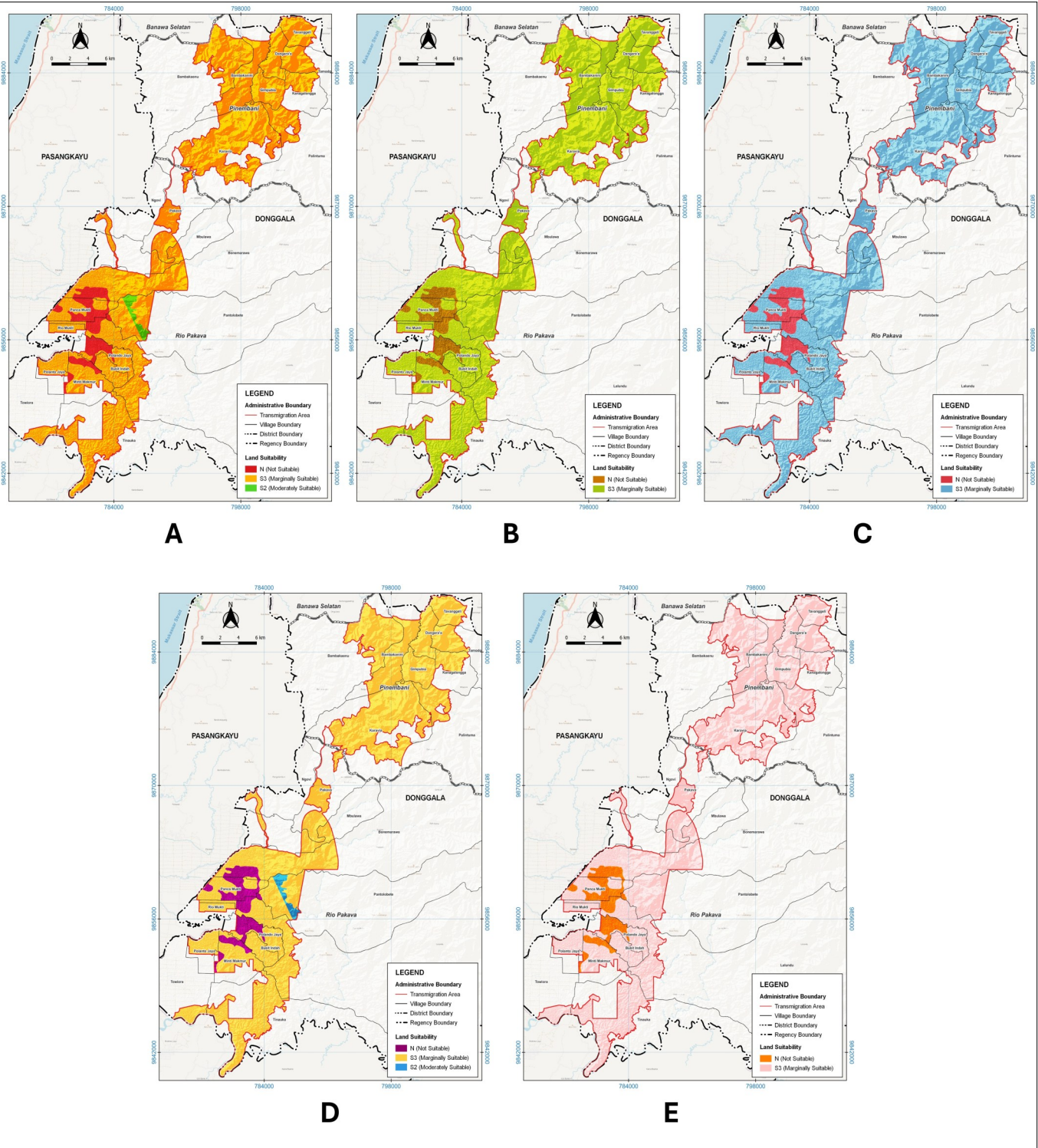


Fig. 4. Actual land suitability maps based on administrative boundary data from BIG (24) and the authors' FAO-based land suitability matching analysis. A: oil palm; B: cocoa; C: durian; D: coconut; E: coffee

Table 4. Distribution of land area (ha and %) by suitability class under actual and potential conditions

Commodity group	Condition	S ₂	S ₃	N
Oil palm and coconut	Actual	362.24 (1.09 %)	30847.97 (92.60 %)	2103.51 (6.31 %)
Oil palm and coconut	Potential	8854.51 (26.59 %)	22355.70 (67.10 %)	2103.51 (6.31 %)
Cocoa, durian and coffee	Actual	—	31210.21 (93.69 %)	2103.51 (6.31 %)
Cocoa, durian and coffee	Potential	—	31210.21 (93.69 %)	2103.51 (6.31 %)

Areas are given in hectares with the percentage of the total study area (33313.72 ha) in parentheses; cocoa, durian and coffee have no S₂ class; the land that is S₂ for oil palm and coconut (LMU 5; 362.24 ha) is classified S₃ for these three crops, so their S₃ area (31210.21 ha) equals the oil palm and coconut S₃ area plus that S₂ area; all class subtotals sum to the total study area.

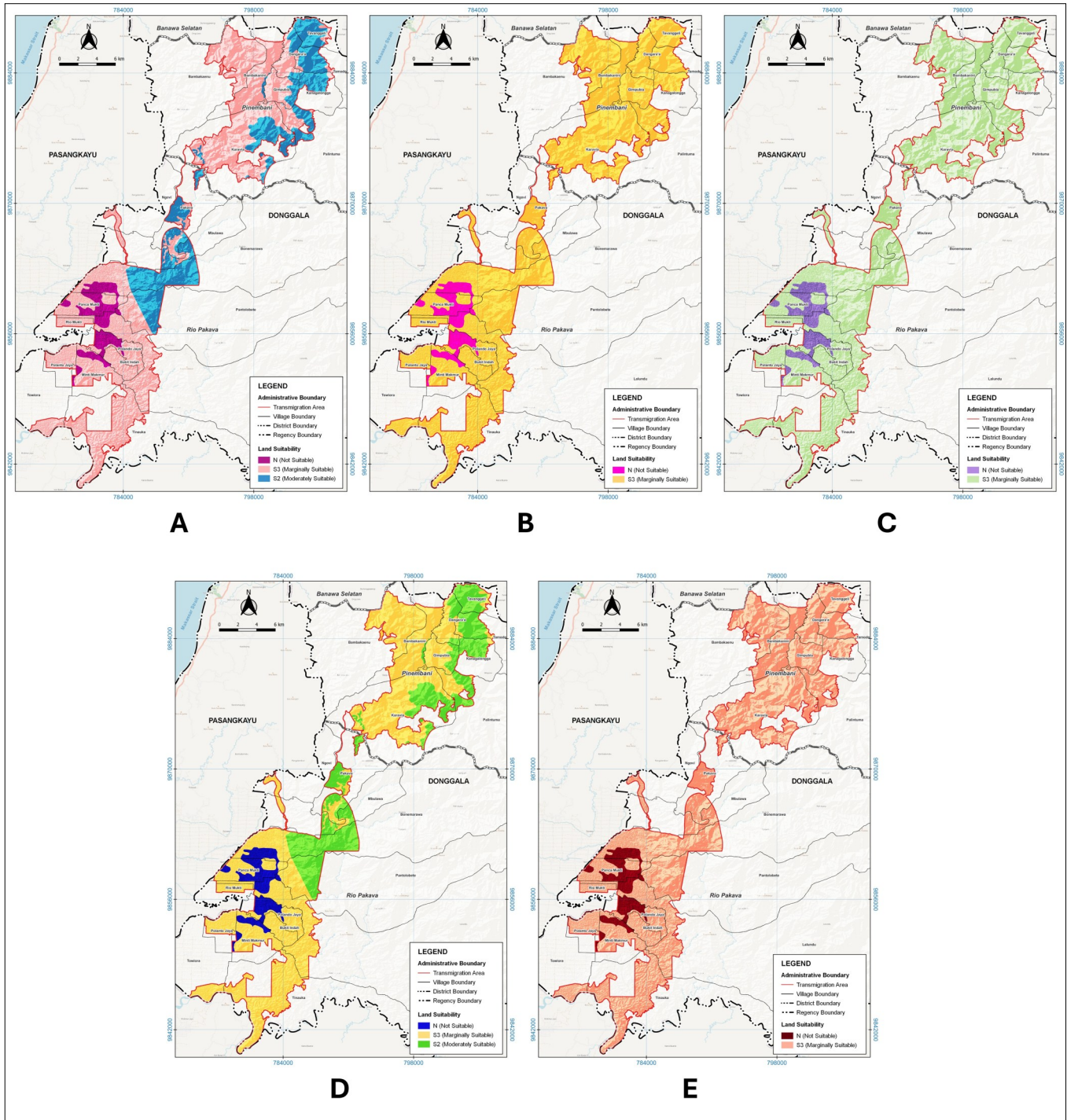


Fig. 5. Potential land suitability maps after feasible land improvement measures based on administrative boundary data from BIG (24) and the authors' analysis. A: oil palm; B: cocoa; C: durian; D: coconut; E: coffee

Economic dominance and flagship-commodity identification

The LQ and SSA results presented in Table 5 were based on production data for 2020–24, shown in Table 6 and obtained from the Central Statistics Agency (BPS) of Donggala Regency (26). Oil palm was the only base commodity among the five in Rio Pakava with a five-year average LQ of 3.58. Production increased from 16848.0 t in 2020 to 19395.4 t in 2024 with a positive net shift (+34.98 %), indicating both comparative and competitive advantage. An LQ of 3.58 indicates that the production concentration of oil palm was more than three times its share at regency level, a level that has been characterised in comparable Indonesian plantation-crop evaluations as established base-commodity status (14). Coconut and coffee were non-base commodities ($LQ < 1$) but exhibited positive growth with net shifts of +2.24 % and +1709.29 %, respectively, placing both in the developing class. Cocoa remained a

non-base commodity with a negative net shift (-150.48 %) and backward status. Durian was not included in the official production statistics for Rio Pakava; therefore, LQ and SSA values could not be calculated and its development potential was assessed qualitatively from field survey observations. Oil palm was positioned in the leading quadrant (Fig. 6a).

An LQ of 3.58 and the fact that approximately 85 % of households rely on oil palm for their livelihoods do not, by themselves, indicate that oil palm is biophysically well suited to Rio Pakava. Rather, these figures are also consistent with the institutional legacy of the PIR-Trans scheme, under which transmigrant households received government-subsidised land parcels, seedlings, tied credit and guaranteed purchase contracts, while nucleus companies provided extension services and milling facilities (36, 37). In Sumatra, independent farmers adopted oil palm most rapidly in

Table 5. Integrated regional economic analysis (LQ and SSA) and resulting commodity typology for the five evaluated commodities

Subdistrict	Commodity	LQ	RSC (%)	PSC (%)	DSC (%)	Net shift (%)	Typology
Rio Pakava	Oil palm	3.58	-4.74	20.11	-0.25	+34.98	Leading (flagship)
Rio Pakava	Coffee	0.05	-4.74	35.34	821.67	+1709.29	Developing
Rio Pakava	Coconut	0.00	-4.74	-14.60	18.09	+2.24	Developing
Rio Pakava	Cocoa	0.15	-4.74	4.51	-77.37	-150.48	Backward
Rio Pakava	Durian ^a	n.a.	n.a.	n.a.	n.a.	n.a.	Potential (field survey)
Pinembani	Cocoa	3.20	-4.74	4.51	347.76	+699.79	Leading (flagship)
Pinembani	Coffee	13.21	-4.74	35.34	-40.07	-14.20	Potential
Pinembani	Durian ^b	11.27	-42.01	90.42	-140.61	-50.19	Potential
Pinembani	Coconut	0.07	-4.74	-14.60	185.81	+337.68	Developing
Pinembani	Oil palm	n.a.	n.a.	n.a.	n.a.	n.a.	Not produced

Values are five-year (2020–2024) results derived from official agricultural production statistics; LQ: location quotient (five-year average); RSC, PSC, DSC: regional share, proportional shift and differential shift components; net shift: PSC + DSC; typology follows the LQ–SSA quadrant: leading (LQ > 1, net shift > 0); potential (LQ > 1, net shift < 0); developing (LQ < 1, net shift > 0); Backward (LQ < 1, net shift < 0). n.a.: not available because the commodity is not recorded in official statistics for that subdistrict (durian in Rio Pakava) or is not produced there (oil palm in Pinembani).

Table 6. Agricultural commodity production (tonnes, (t)) in Rio Pakava and Pinembani subdistricts and Donggala Regency, 2020–2024

Rio Pakava subdistrict					
Commodity	2020	2021	2022	2023	2024
Coconut	0.8	158.8	0.8	0.9	0.8
Oil palm	16848.0	17408.8	17099.8	17248.2	19395.4
Coffee	2.6	2.6	2.6	3.0	25.1
Cocoa	1138.8	1138.8	255.0	1138.8	255.0
Durian	0.0	0.0	0.0	150.0	321.7
Pinembani subdistrict					
Commodity	2020	2021	2022	2023	2024
Coconut	15.0	38.0	15.0	12.0	40.0
Oil palm	0.0	0.0	0.0	0.0	0.0
Coffee	52.8	52.8	52.8	91.9	47.8
Cocoa	230.2	1026.2	1030.2	1098.8	1030.2
Durian	100.0	244.0	14.0	6.0	7.8
Donggala Regency					
Commodity	2020	2021	2022	2023	2024
Coconut	29609.0	33084.6	29293.8	32232.2	23881.8
Oil palm	16867.1	17586.7	17160.9	17325.2	19459.5
Coffee	355.0	378.5	363.3	493.6	463.6
Cocoa	17880.1	21544.1	17318.0	17943.7	17837.8
Durian	584.0	625.9	440.0	499.0	866.7

Processed from the Central Statistics Agency (BPS) of Donggala Regency, 2025 (26)

villages where contract and out-grower schemes were already established, creating regional path dependency that continued to influence production patterns decades after the original policy interventions (38). Mill location further reinforces this pattern because fresh fruit bunches must reach a processor within 24–48 hr to avoid quality penalties, thereby encouraging smallholders to cultivate oil palm irrespective of alternative crops that the land could support agronomically (39). In Rio Pakava, a private nucleus estate operated by PT Lestari Tani Teladan, a subsidiary of Astra Agro Lestari, has been operating since 1993, supported by a fresh-fruit-bunch mill. Since 2006, smallholder adoption has been promoted through the company's income generating activity seedling-loan partnership. Oil palm dominance in the area may therefore reflect, at least in part, the cumulative effects of these historical land-allocation and market-access arrangements.

The integrated framework cannot distinguish between these pathways because the LQ measures production concentration without capturing its institutional origin. Its contribution lies elsewhere: the biophysical analysis confirms that the land supports

oil palm at a minimum suitability level of S_3 or above across most LMUs, an assessment that production statistics and policy history alone cannot supply. Where institutional path dependency coincides with biophysical feasibility, the flagship designation is supported. Conversely, if oil palm had become established on land classified as N, the integrated approach would have identified that mismatch. No such mismatch was observed. Oil palm therefore qualifies as the flagship commodity for Lalundu on both biophysical and economic grounds, with the caveat that the LQ reflects accumulated policy decisions as well as the natural comparative advantage afforded by the land.

In Pinembani, cocoa, coffee and durian were all base commodities (LQ = 3.20, 13.21 and 11.27, respectively). Only cocoa combined base status with a positive net shift (+699.79 %), the highest recorded in the dataset. Coffee and durian remained base commodities but exhibited negative net shifts (net shifts -14.20 % and -50.19 %, respectively) and were classified in the potential class, whereas coconut was classified as developing (LQ = 0.07, net shift +337.68 %). Oil palm was not cultivated in Pinembani. A net shift of

+699.79% indicates that cocoa production in Pinembani exceeded the district growth trend by a greater margin than any other commodity included in the analysis. Comparable studies in Sulawesi have shown that experienced smallholder networks and targeted management can produce similar competitive growth responses in cocoa production (29). Cocoa occupied the leading quadrant in Pinembani (Fig. 6b), while Fig. 6 compares the economic performance of both subdistricts.

Location quotient alone is insufficient for flagship commodity selection. Coffee and durian in Pinembani recorded the highest LQ values in the dataset (13.21 and 11.27, respectively), yet both exhibited declining competitiveness, with net shifts of -14.20% and -50.19%, respectively. The LQ captures structural production concentration accumulated over the study period, whereas SSA separates current competitive performance from the broader district growth trend (40). A commodity can maintain a high LQ while

exhibiting a negative differential shift, indicating that local conditions no longer confer above-average competitiveness. Coffee and durian in Pinembani both exhibited this pattern and previous LQ-SSA studies of Indonesian plantation commodities have similarly reported that base-commodity status and competitive growth are frequently misaligned (41). In contrast, coffee in Rio Pakava recorded the highest growth rate in the analysis (net shift +1709.29%) but remained a non-base commodity (LQ = 0.05) on land with severe biophysical constraints. Consequently, neither commodity qualified as a flagship. Flagship designation therefore requires evidence of production concentration, competitive growth and land capability.

Oil palm in Lalundu and cocoa in Bambakaenu satisfied all three criteria. Both were predominantly classified as S_3 , indicating that cultivation is feasible despite constraints related to water availability, rooting conditions, nutrient availability and erosion hazard which vary among LMUs and can only partly be mitigated

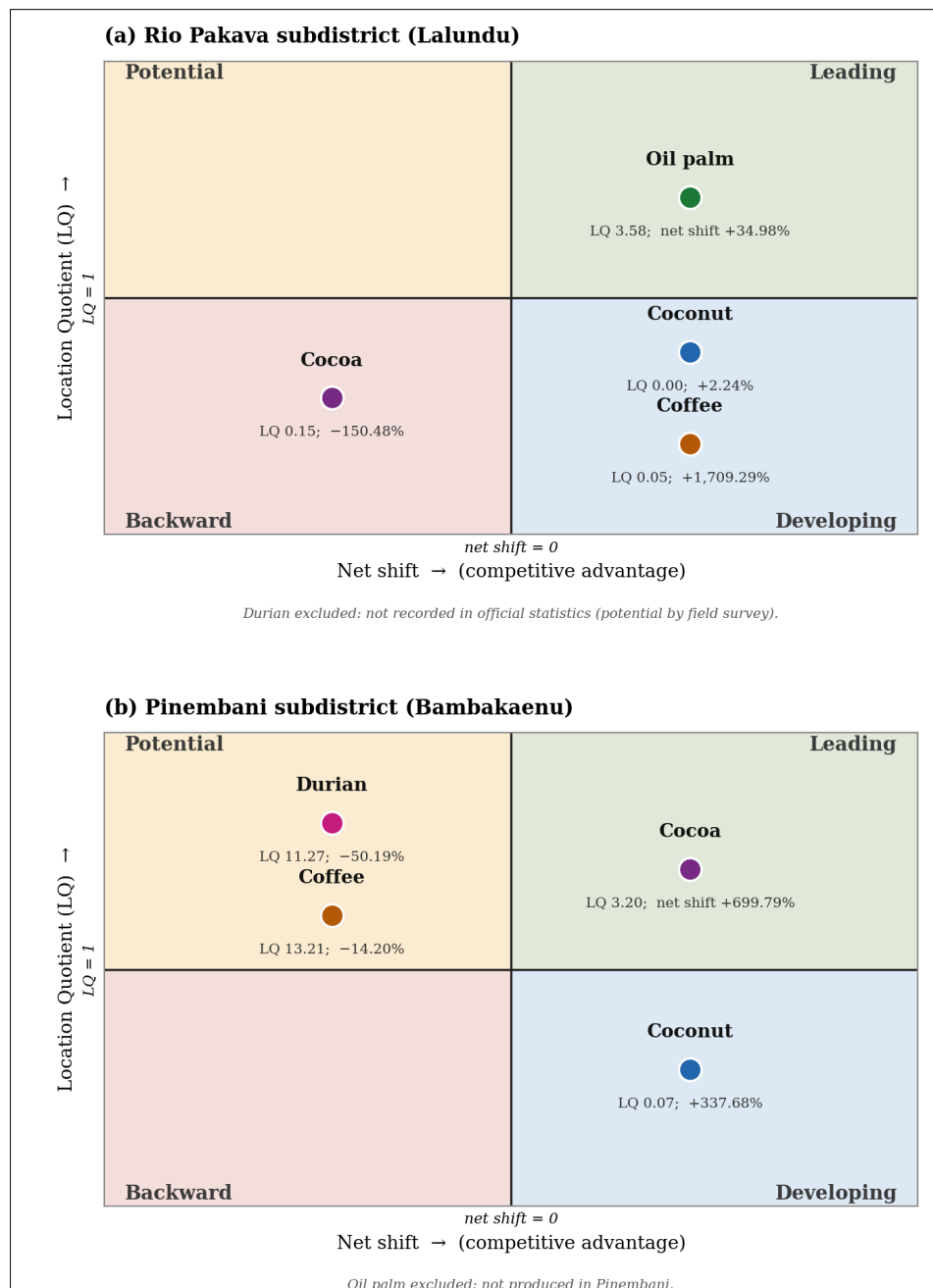


Fig. 6. Commodity typology combining location quotient (LQ) and shift-share analysis (SSA). a: Rio Pakava subdistrict (Lalundu); b: Pinembani subdistrict (Bambakaenu); the vertical axis plots comparative advantage (LQ; threshold = 1) and the horizontal axis plots competitive advantage (net shift; threshold = 0), forming four quadrants: leading, potential, developing and backward; point positions are schematic; exact LQ and net-shift values are annotated.

through management. With an LQ above one and a positive net shift, both commodities demonstrated comparative and competitive advantages within their respective subdistricts. Oil palm contributes substantially to household income stability that short-term diversification rarely replaces; about 85 % of households in Rio Pakava depend on it as their primary livelihood source (42). Sulawesi remains Indonesia's leading cocoa-producing island and growers in Pinembani have participated in this production system for decades, benefiting from established market linkages and accumulated production experience. Applying land suitability as a minimum-viability filter alongside LQ and SSA avoids the two major misclassification risks (the high-LQ/declining-competitiveness case and the high-growth/non-base case) and provides more robust flagship designations than either approach alone (13). Overall, the results support the study hypothesis.

Management and policy implications

Management should target attainable productivity within existing constraints, with priorities determined by the dominant limiting factor in each LMU. Selected LMUs could attain S_2 for oil palm and coconut through phosphorus application, erosion-control measures on sloping land and soil and water conservation. However, these interventions do not alter the permanent limitations imposed by rainfall, relative humidity, soil texture, effective soil depth and slope gradient. On the acidic soils of the study area (pH as low as 4.47), iron and aluminium oxides reduce phosphorus availability to oil palm; targeted phosphorus application in the P-limited LMUs (na constraint) addresses this constraint at the site level (27). On slopes of up to 29 %, conservation tillage and ground-cover establishment reduce erosion losses that would otherwise degrade the rooting zone available to oil palm and coconut (32).

For cocoa, management priorities include organic matter addition, liming, potassium fertilisation, soil moisture conservation and erosion control. Since water availability is a permanent limitation, rainwater harvesting, shade management and mulching are most effective when combined with fertilisation. A field trial on marginal acidic soil in South Sulawesi directly supports this integrated approach: cocoa trees treated with compost produced five times the dry bean yield of untreated controls after 20 months, whereas mineral fertiliser or dolomite applied alone was insufficient and was associated with 22–45 % tree mortality (43). This response is largely explained by improvements in soil properties. Compost enhances pH buffering, cation availability and water-holding capacity simultaneously, thereby addressing multiple constraints that individual chemical inputs resolve only separately. Shade trees reduce canopy evapotranspiration and contribute organic inputs that improve soil moisture retention, making shade management an integral component of water conservation on predominantly S_3 land. Although these practices rarely improve the formal suitability class, but they reduce production risk and enhance resilience of cropping systems on marginal land.

At the planning level, units classified as N, of which LMU 6 is the clearest example, require explicit spatial zoning. Flagship commodity development should exclude these units, which are more appropriately allocated to conservation, protective vegetation, or other low-impact land uses rather than agricultural expansion. Indonesian land-use studies classify very shallow soils as protection-function areas rather than agricultural land (35). Treating LMU 6 as suitable for development simply because it occupies a small area

and is surrounded by predominantly S_3 land would represent the type of spatially undifferentiated planning that transmigration programmes should avoid.

Limitations

These findings should be interpreted in light of four limitations. First, the most-limiting-factor rule favours conservative suitability classes and the resulting classifications are sensitive to the threshold values applied. Second, the 10-year climate averages (2015–24) may not fully capture the influence of extreme climatic events. Third, the economic analysis depends on official production statistics, which may contain reporting inconsistencies; in addition, SSA results are sensitive to the choice of baseline year, the analysis period and commodities with very low baseline production. Finally, the identification of flagship commodities is based on production concentration and growth dynamics rather than economic returns, profitability or household income, which they require additional data sources. Farm-gate prices, market access, value-chain performance and household welfare metrics should therefore be incorporated into future assessments to provide a more comprehensive evaluation of livelihood outcomes.

Conclusion

Combining Food and Agriculture Organization of the United Nations (FAO)-based land suitability evaluation with location quotient (LQ) and shift-share analysis (SSA) produced more robust flagship commodity designations than either approach alone, as a high LQ can mask declining competitiveness, whereas strong production growth can occur on land that is not biophysically suitable for sustained cultivation. Water availability, rooting conditions, nutrient availability, nutrient retention and erosion hazard limited all five commodities to S_3 across most of the study area. The land mapping unit 6, classified as unsuitable (N) for all five commodities, should be excluded from development planning. Oil palm in Lalundu (LQ = 3.58, net shift +34.98 %) and cocoa in Bambakaenu (LQ = 3.20, net shift +699.79 %) each satisfied the minimum biophysical suitability threshold while demonstrating comparative and competitive economic advantages. Reliable flagship commodity selection on marginal land requires the integrated assessment of land suitability and economic performance. Spatial zoning should therefore direct development towards units classified as S_3 or higher while excluding those classified as N.

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Authors' contributions

MIF conceived and designed the study, coordinated the overall research framework, supervised data collection and analysis and led the writing and revision of the manuscript. MN conducted field surveys, collected primary data, contributed to data interpretation and participated substantially in drafting the manuscript. SANF performed spatial data processing, GIS analysis and contributing to the interpretation of land suitability results. NTN assisted in data compilation and statistical processing and supported the interpretation of economic analysis results. ADAY contributed to manuscript editing. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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