



Assessment of Land Suitability in Perennial Crops using FAHP and GIS in Central Vietnam

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ABSTRACT

Background: Perennial crops including rubber and Thanh Tra grapefruit are highly effective land use that has occupied a large area (nearly 11,000 ha) in Thua Thien Hue province, Central Vietnam. Analyzing land suitability in agricultural production is one of the important tools for determining the effective use of land resources and sustainable development. This study aims to evaluate the land suitability of perennial crops in Phong Dien district, Thua Thien Hue province, Central Vietnam.

Methods: The study was conducted in different communes in Phong Dien district, Thua Thien Hue province, Central Vietnam from 2022 to 2023 by collecting secondary and primary data together with soil samples from 45 profiles for analysis and finally application of the fuzzy multi-criteria analysis process (FAHP) tool and geographic information system method (GIS) to evaluate the land suitability.

Result: The results indicated that economic criteria played the most important role with weights from 0.068 to 0.343, followed by the social criteria (weights from 0.014 to 0.147) and the environmental criteria (weights from 0.011 to 0.051). With land suitability evaluation, the very high suitability area of rubber and Thanh Tra grapefruit (S1) was 3,144.14 ha and 3,742.29 ha respectively. The FAHP and GIS integrated method is a useful method to assess land suitability for land use of perennial crops based on appropriate assessment of FAO land use requirements.

Key words: FHAP, GIS, Land evaluation, Perennial crops.

INTRODUCTION

Assessing land suitability, thereby selecting effective land use types for reasonable use from the perspective of ecology and sustainable development, is becoming a global issue of interest to scientists around the world (Nguyen Van Binh, 2017). Land suitability assessment is carried out by combining land characteristics with land use requirements (Herzberg *et al.*, 2019) which is necessary to match land resources and land uses properly, effectively and reasonable way (Pereira *et al.*, 2017; Li *et al.*, 2012). In addition, land assessment is necessary for land use planners to avoid costly mistakes and improve investment efficiency (Mohammed *et al.*, 2020) as well as the sustainability of crop production.

Geographic information system (GIS) is a powerful tool for storing, retrieving, processing and analyzing multi-source spatial/temporal data necessary for spatial planning and management (Singh *et al.*, 2017). However, GIS does not consider criteria priorities because all criteria are not equally important (Gigović *et al.*, 2017). Analytical Hierarchy Process (AHP) is a multi-criteria method for assessing land use suitability based on Geographic Information System (GIS). AHP is one of the popular methods widely used to solve multi-criteria decision-making (MCDM) problems (Rane *et al.*, 2023). Fuzzy sets are used in AHP calculations to compensate for this shortcoming (Rathia *et al.*, 2015). Furthermore, those methods are proven to be flexible, effective and robust approaches in the field of land suitability (Xu and Zhang, 2013) when generating feasible land suitability

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map options (Van Chuong Huynh, 2008) ranked according to experts' preferences (Qureshi *et al.*, 2018).

Central Vietnam is considered the most difficult area in Vietnam. The effective management of land resources for agricultural production in this area is an essential requirement for food security and sustainable rural development. The inappropriate use of agricultural land is a major constraint to agricultural production in Vietnam (Herzberg *et al.*, 2019). This paper integrates GIS and FAHP methods to determine the land suitability for rubber and Thanh Tra grapefruit in Thua Thien Hue province, Central Vietnam.

MATERIALS AND METHODS

Study area

The study area was carried out in Phong Dien district (16°35'41"-16°57'00"N and 107°3'00"-107°21'4"E), Thua

Thien Hue province, Central Vietnam. This district includes 16 administrative units with a total natural land area of 94,566.10 ha, accounting for 18.89% of the natural land area of Thua Thien Hue province (Fig 1).

Data collection

Secondary data was collected from different Departments such as Natural Resources and Environment, Agriculture and Rural Development including natural conditions, socio-economic reports, land use and from reports, papers in 2022. Primary data was collected by the Participatory Rural Appraisal method (PRA) following the questionnaire in 2023. The number of interviewed households was applied according to the formula of Slovin (1960) with 160 people in 16 towns and communes in the Phong Dien district. The content of direct interview questionnaires was input costs, output costs, technical practices, productivity, capital sources and consumption markets, for each type of land use. We also asked opinions from 35 scientists, experts from universities and research institutes and experienced managers in the field of land management regarding the importance of criteria in the FAHP evaluation method.

Soil collection and analysis

Based on soil classification results from the soil map of Thua Thien Hue province at a scale of 1/50,000, the soil map of Phong Dien district at a scale of 1/25,000 (Phong Dien District People's Committee, 2020), soil types in the study area were investigated through survey, soil profile making, description, sampling and analysis. 45 soil profiles including 62 samples were taken according to FAO - UNESCO guidelines for analysis in all communes of Phong Dien district, Thua Thien Hue province with properties including pH_{KCl} , OM, total N, total P_2O_5 , total K_2O , available N, available P_2O_5 , available K_2O according to standard methods (Page *et al.*, 1996). Soil analysis results indicated pH_{KCl} (4.46), OM (2.15%), total N (0.083%), total P (0.026%), total K (4.88 mg/100 g), available N (4.88 mg/100 g), available P (2.86 mg/100 g), available K (16.26 mg/100 g) and soil texture with sandy to loamy.

Methods of building land map unit

To evaluate the suitability for land use, we constructed a map of Phong Dien district's land unit at a scale of 1/25,000 as a basis for land assessment (FAO, 1976). The land map unit (LMU) is a component of the land use system in land assessment. Based on the actual conditions of Phong Dien district, we chose 6 main criteria to build an LMU including soil type (17 types), slope (6 slopes), soil texture (4 textures), soil fertility (3 fertility levels), irrigation (3 regimes), soil horizon (5 depths). These thematic maps were built based on soil maps, topographic map, hydrological system map, agricultural land use map and soil analysis results from 45 soil profiles. Thematic maps were established at a scale of 1/25,000 according to the coordinate system, reference system VN-2000 and meridian axis 107° specified for Thua Thien Hue province (Fig 2). After overlapping the thematic maps, we had a land unit map of Phong Dien district, Thua Thien Hue province at a scale of 1/25,000. These diagnostic factors (land use requirements) are the basis for comparing and contrasting the land quality of each LMU, thereby determining the appropriate levels of the selected LUTs. The consideration between limiting factors and normal factors can be improved in the process of comparing and evaluating the suitability of each LUT according to the LMUs studied in the region follows the soil assessment process according to FAO (Nguyen Van Binh, 2017).

FAHP method in suitability assessment

The Fuzzy Analytic Hierarchy Process (FAHP) method was applied following Pilevar *et al.* (2020). The main criteria in assessing the suitability of perennial crops (rubber, Thanh Tra grapefruit) were economic, social and environmental. The economic calculation included gross output (GO), intermediate costs (IC) and value-added (VA). Social and environmental effectiveness was evaluated through survey data to standardize the Xi value classification scale of each criterion for selected land use types according to each study area in the future. There was an additional criterion for

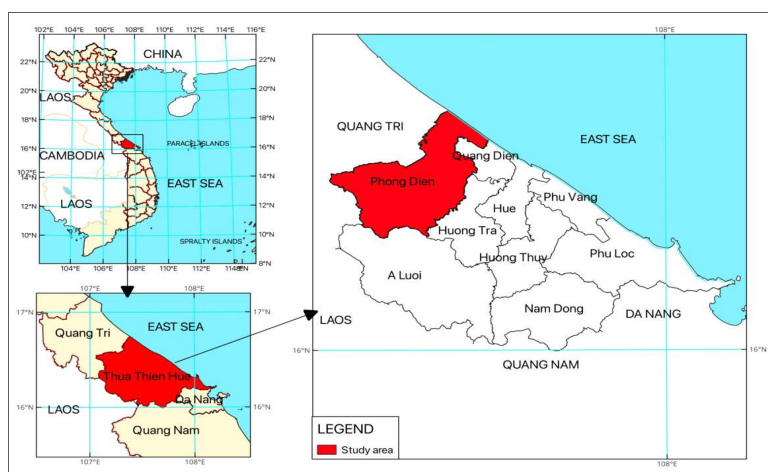


Fig 1: Map of research location.

decentralization content, which was the ability to consume products (additional decentralization criteria: transportation system, proximity to commercial areas, markets), the criteria were divided into 4 levels. According to Nguyen Van Binh (2017) and Van Chuong Huynh (2008), the X_i value classification of each criterion was ranked by points, varying from 3 to 9. Social and environmental indicators were a layer of thematic information, then overlaid those layers of information with the support of GIS technology and the fuzzy multi-criteria method (FAHP) to assess social and environmental appropriateness (Tadele *et al.*, 2022). The sub-criteria of land use requirement in the main criteria did not consider unsuitable land units (N) for each land use type in perennial crops, only applying to units from S1, S2 and S3 levels.

The prioritization of sustainability S_i levels was carried out using the AHP method of Saaty (1980). The data processing was done by using Excel software 2016, analyzing expert opinions and referring to the prioritization results provided by Nguyen Van Binh (2017) and Van Chuong Huynh (2008).

Based on the LMU, we evaluated and established land suitability maps for each land use type for perennial crops (Thanh Tra grapefruit, rubber). According to FAO's assessment framework (FAO, 1976), the GIS included 11 data fields, *i.e.* soil type, slope, soil texture, soil horizon, fertility, commune, district, classification of suitable land use requirements, area and notes. The ID data field considered land units of evaluated land use types from 1-111. Based on the attribute data of each land suitability map, we converted data from GIS to Excel to process FAHP. FHAP was built and calculated in Excel with 3 main criteria and 12 sub-criteria through questionnaires of calculation results and experts for 2 types of perennial crops. Through the global weight (W_i) and score (X_i) of each criterion, the results were evaluated for each land unit, each commune-

level administrative unit in the entire Phong Dien district, Thua Thien Hue province of two types of perennial land use (Thanh Tra grapefruit, rubber).

RESULTS AND DISCUSSION

Assessment of land suitability according to land use requirements

The result of overlaying single-dimensional maps of the study area resulted in a land unit map for Phong Dien district aiming at land suitability assessment and land use orientation (Fig 3). There was a total of 111 land unit maps in Phong Dien district from 17 soil types, this reflected a great diversity and difference of soil types in the study area in which coastal sandy soil, alluvial soil on sandstone, alluvial soil, red-yellow soil on metamorphic rocks, deep active alum soil, moderate salinity soil, gray soil on acidic magmatic rocks, red yellow humus soil on magma rock, red and yellow loamy soil on metamorphic rock, had the least number of land units and only one land unit. Similar results were found in Herzberg *et al.* (2019) and Hoang *et al.* (2022) who indicated that the implemented methodology of land suitability evaluation proved to be an appropriate and useful approach for the application in a hilly district of Vietnam. In the Vietnam uplands, social and economic characteristics had a significant impact on agricultural land use.

Results of assessing the suitability level of LUT1 (Thanh Tra grapefruit) (Table 1) indicated that the area of high suitability level (S1) was 7,908.64 ha with land units no. 2, 8, 17, 21, 32, 33, 41, 70, 74, 76, 79, 82, 83, 85, 87, 93, 107 accounting for 8.36% of the total natural area of the study area. At the suitability level (S2), the area was 3,610.09 ha, accounting for 3.82% of the total natural area of the study area. For the suitability level (S3), the area was 17,740.23 ha, accounting for 18.76% of the total natural area of the study area. The remaining unsuitable level (N), accounts for

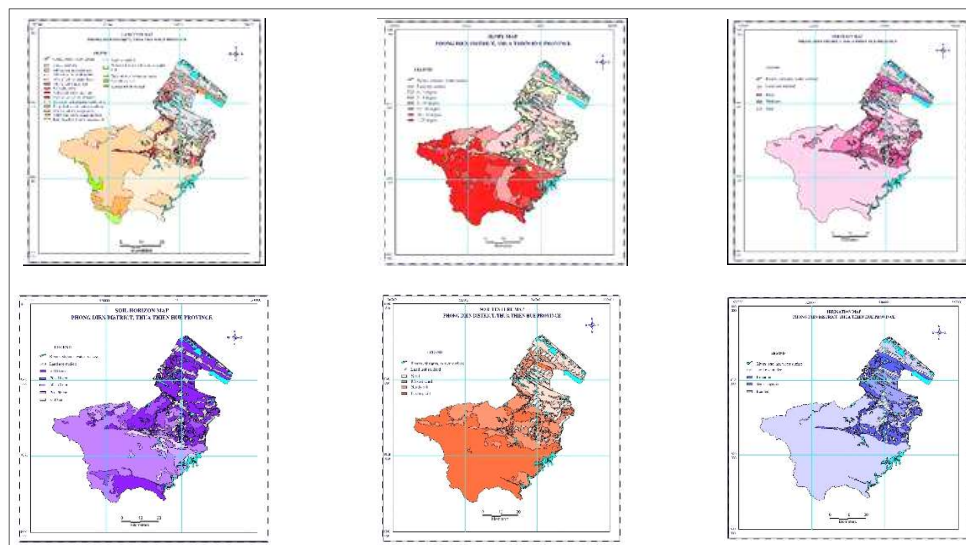


Fig 2: Thematic maps.

53,434.95 ha (56.47% of the total natural area in land units no. 1-8, 13-23, 27-39, 41-43, 45, 47-49, 53-66, 70-72, 74, 76-80, 83, 85-87, 102). Land types have not been included in the assessment as non-agricultural land (8,356.42 ha), rivers, streams, or specific water surfaces (3,515.78 ha). Limiting factors of this LUT included soil type, slope, soil horizon and soil texture. Similarly, LUT2 (rubber) (Table 1), with an area of 1,427.95 ha at the suitability level (S1) belonged to land unit no. 82, 106, 107, 110, 111. Suitability level (S2) had an area of 7,726.97 ha, accounting for 8.17% of the total natural area, belonging to land units no. 25, 40, 68-69, 73, 89-97, 101, 104-105 and 108. Suitability level (S3) had an area of 9,197.86 ha, accounting for 9.73% of the total natural area with land unit no. 9-12, 22, 24, 26, 44, 50-51, 67, 75, 81, 84, 98-100, 103, 109. There was a remaining 64,341.13 ha, accounting for 68.04% of the total natural area at an unsuitable level (N). Limiting factors of

this LUT included soil type, slope and soil horizon. The study area belonged to a hilly area in Vietnam where characterized by numerous natural, economic and social factors that made it unsuitable for agricultural production. Physical constraints including high elevation, soil acidity and low soil nitrogen were the primary barriers to agricultural production, particularly for economic crops like grapefruit and rubber. Fallow farming, high rates of erosion and population pressure were all negatively impacted on sustainable agriculture (Herzberg *et al.*, 2019). The land with the lowest rates of poverty, the most access to knowledge and the highest concentration of farming expertise is best suited for the assessed crops. These socioeconomic circumstances were essential to the production of bananas and rubber. For example, a significant level of technological expertise was required for the planting of rubber trees, the collection of latex and the creation of a transportable rubber product (To and Tran, 2018; Nguyen, 2018). Farmers still had a limited understanding of new commercial crops compared to cassava and upland rice (Fox, 2014).

Table 1: Summary data on suitability assessment of land use requirements for land use types in Phong Dien district.

Appropriate level required using land	Types of land use (ha)	
	LUT1	LUT2
Integration level S1	7,908.64	1,427.95
Integration level S2	3,610.09	7,726.97
Integration level S3	17,740.23	9,197.86
Unsuitable level of integration	53,434.95	64,341.13
No studied land	8,356.42	8,356.42
Rivers, streams, water surface	3,515.78	3,515.78
Total	94,566.10	94,566.10

LUT1: Thanh Tra grapefruit; LUT2: Rubber.

Applying FAHP and GIS to evaluate the suitability of perennial land use types

With a pairwise comparison matrix of the main criteria: Economy, society, environment and the weights of the factors were calculated and established a matrix for each sub-criteria of the above main criteria. Thus, the criteria in the suitability assessment determined all partial weights according to the main and secondary criteria. The global weight of the criteria (main and secondary) in suitability assessment was based on the product of the weight of the

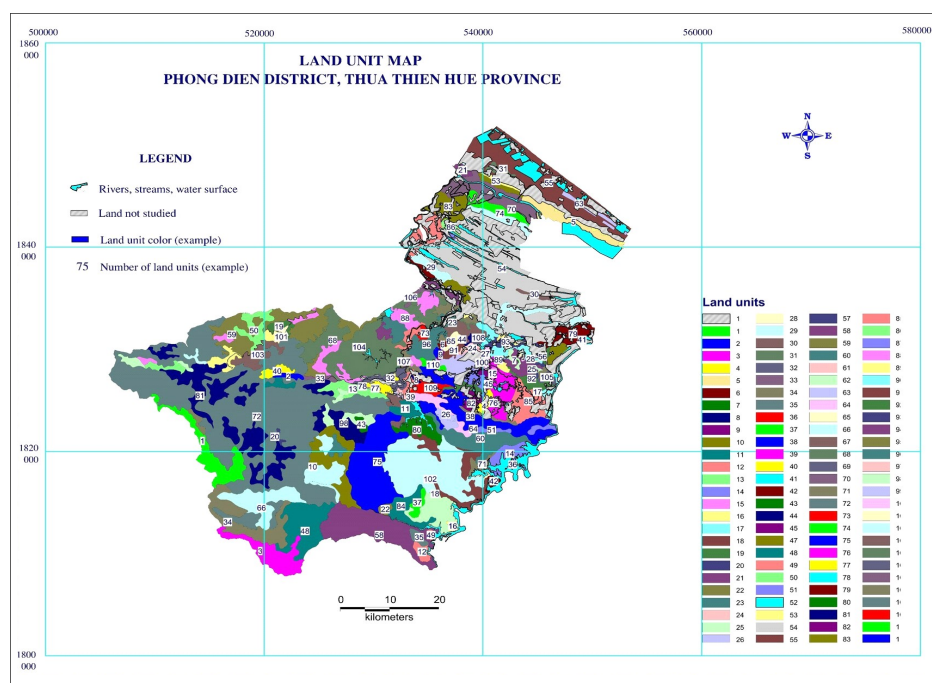


Fig 3: Map of land units of Phong Dien district, Thua Thien Hue province.

Table 2: Global weights of rubber and Thanh Tra grapefruit land use types.

Main criteria	Component of subcriteria	LUT1			LUT2			
		Weight (W_{1i})	Weight (W_{2i})	Global weight ($W_i=W_{1i} * W_{2i}$)	Weight (W_{1i})	Weight (W_{2i})	Global weight ($W_i=W_{1i} * W_{2i}$)	
1. Economy	Production value	0.566	0.273	0.154	0.629	0.345	0.217	
	Added value		0.607	0.343		0.512	0.322	
	Production efficiency		0.121	0.068		0.143	0.090	
2. Society	Working day	0.324	0.145	0.047	0.263	0.316	0.083	
	Product consumption		0.454	0.147		0.400	0.105	
	Attract labor		0.226	0.073		0.153	0.040	
	Consistent with customs		0.114	0.037		0.079	0.021	
	Development policy		0.060	0.020		0.052	0.014	
3. Environment	Covering ability	0.110	0.100	0.011	0.107	0.204	0.022	
	Maintain and improve soil fertility		0.146	0.016		0.153	0.016	
	Level of use of fertilizers and pesticides		0.292	0.032		0.238	0.026	
	Suitable for land use		0.463	0.051		0.405	0.043	
			CI=0.0018	RI= 0.580	CI=0.0194			RI= 0.580
			CR=0.0032		CR=0.0334			

Note: W_{1i} : Main criteria; W_{2i} : Sub criteria; CR: Consistency ratio; CI: Consistency index; RI: Random index.

Table 3: Summary results of suitability assessment on rubber and Thanh Tra grapefruit land use types.

Adequate level of sustainability	Land use types (ha)	
	LUT1	LUT2
Integration level S1	3,742.29	3,144.14
Integration level S2	8,399.49	2,630.78
Integration level S3	17,117.18	12,577.86
Integration level N	53,434.95	64,341.13
Land not studied	8,356.42	8,356.42
Rivers, streams, water surface	3,515.78	3,515.78
Total	94,566.10	94,566.10

main criterion and sub-criteria of each criterion for each land unit of the criteria.

$$W_i = W_{1i} \times W_{2i}$$

Among the main criteria (W_{1i}) in the rubber tree (Table 2), the economic criterion has the highest weight (0.629) and conversely, the environmental criterion has the lowest weight (0.107). This means that the economic criterion is the most important in assessing the sustainability of this type of land use. Among the sub-criteria (component W_{2i}), the added value criteria have the highest weight (0.512) compared to the other two criteria. Regarding the overall weight W_i of the sub-criteria (component W_i), the economic criterion still plays the most important role in assessing suitability (0.090-0.322) compared to the remaining social and environmental criteria. In the FAHP sustainability assessment for this type, CR = 0.0334 (<0.1), proving that the results ensure accuracy and are consistent with FAHP standards. Similar to rubber trees, it is also found that in the main criteria (W_{1i}), the highest and lowest weights

(0.566 and 0.110) are in the economic and the environmental criteria for Thanh Tra grapefruit, respectively. The product consumption criterion has the highest weight (0.454) compared to the other 4 sub-criteria. In the overall weight W_i of the sub-criteria (component W_{2i}), the economic criteria also play the most important role in assessing sustainability (0.068-0.343) compared to the remaining social and environmental sub-criteria of this land use type. The result of this type has CR=0.0032 (<0.1), ensuring reliability when assessed by FAHP.

The results of the suitability assessment of land use types by each land unit of Phong Dien district are shown in Fig 4. With an area of 3,742.29 ha, 8,399.49 ha and 17,117.18 ha was found in LUT 1 (Thanh Tra grapefruit) for very high suitability level (S1), high suitability level (S2) and low suitability level (S3), respectively. Level of S1, S2 and S3 in LUT2 (rubber) were 3,144.14 ha, 2,630.78 ha and 12,577.86 ha.

The results in Table 3 compared to suitable land use requirements, area of high suitability level (S1) for LUT2 increased significantly to 1,716.19 ha, because these areas had very large consumer markets, convenient access to capital and very good techniques, etc. On the contrary, there was affected by weather impacts and consumer markets, etc. Therefore, the area of high suitability level (S1) in LUT1 decreased by 4,166.35 ha compared to suitable land use requirements. Suitability levels of S2 and S3 had an increase and decrease in area between LUTs because these areas had very favorable consumption markets, favorable access to capital and very good technology. However, there were also some LMU were highly suitable in terms of land (land use requirements) but low suitability level.

There was no change in the area of unsuitability level (N) when assessing suitability for land use requirements

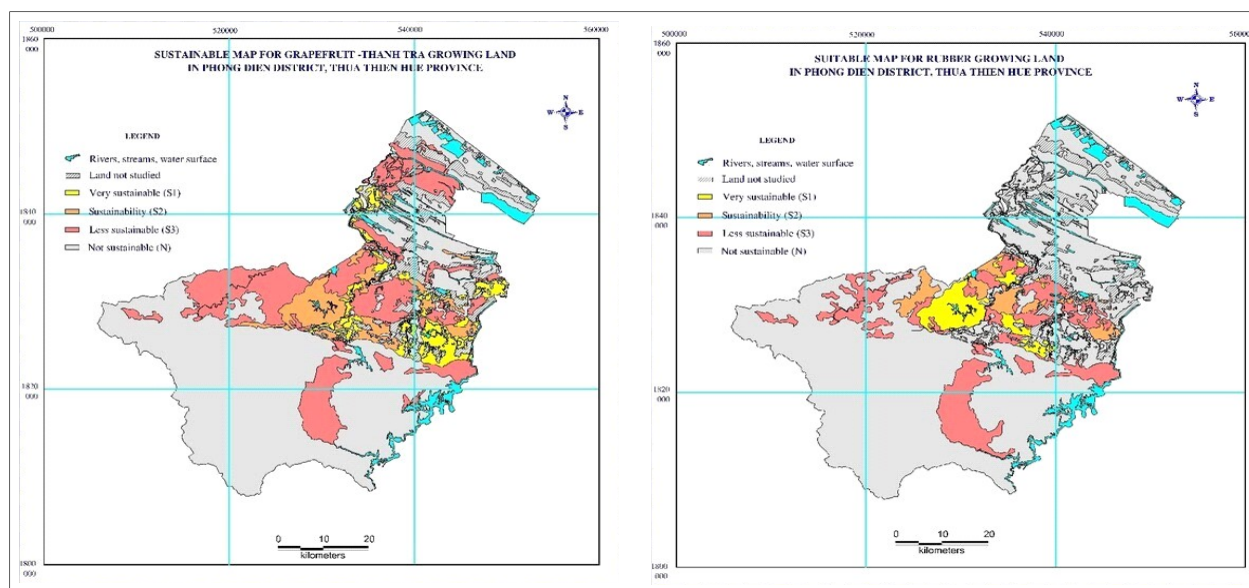


Fig 4: Map assessing the sustainability of Thanh Tra grapefruit (LUT1) and rubber (LUT2).

and suitability level in Phong Dien district, Thua Thien Hue province.

In previous studies, land suitability is often assessed in terms of natural (environmental) factors for agricultural land such as the suitability of agricultural land (Pilevar *et al.*, 2020; Ramamurthy *et al.*, 2020; Sengupta *et al.*, 2022), which placed great emphasis on topography, soil, climate, accessibility and land use. Saha *et al.* (2021) reported that soil, climate and topographic characteristics were considered in the study. Evidence from model output, 29,534 ha (30.54%), 34,984.74 ha (36.17%), 17,455 ha (18.05%), 14,744.61 ha (15.24%) were ranged in moderately suitable, slightly suitable, currently unsuitable and permanently unsuitable, suitable for sorghum production. Slope gradient, elevation, temperature, growing time, available water capacity, average gravimetric diameter, total nitrogen, available phosphorus and soil organic carbon content are considered. The fuzzy-AHP suitability assessment model was adapted to determine the weights for topographic and soil properties (Sonia *et al.*, 2023). The highest specific weights were obtained for soil depth (0.232) and elevation (0.218), while the lowest weight was calculated for aspect (0.042). Highly, moderately and marginally suitable lands for wheat cultivation cover 2.63, 9.85 and 32.59% of the study area, respectively. In addition, the results indicated that 54.92% of the total area is permanently unsuitable for wheat cultivation (Kilic *et al.*, 2022). Similar results were found by Sonia *et al.* (2023) and Yousif *et al.* (2020). FAHP and GIS integrated approach is a convenient and effective assessment method, commonly applied to assess land suitability (Sarkar *et al.*, 2021; Li *et al.*, 2022).

CONCLUSION

In summary, the FAHP and GIS integrated method was a useful method to assess land suitability for perennial crop land use types based on appropriate assessment of land

use requirements from FAO combined with 3 criteria, *i.e.* economic, social and environmental in study site. The study built a map of land units in Phong Dien district on the basis of overlapping 6 factors (soil type, slope, soil horizon, soil texture, fertility, irrigation regime) and identified 111 units. The results of assessing the suitability of the three economic, social and environmental aspects based on the combination of GIS and FAHP, the area of S1 level for Thanh Tra grapefruit land use type increased significantly. A sharp decrease the area of S1 level for rubber land use type. Relevance levels of S2 and S3 had an increase and decrease in area between LUTs. This study has proposed an effective approach in land suitability assessment by integrating the FAHP and GIS to increase land use efficiency, ensuring sustainable development of perennial crops in Phong Dien district in particular and Thua Thien Hue province and the Central region in general.

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Conflict of interest

All authors declare that they have no conflicts of interest.

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