Soil Properties Mapping and Land Evaluation for Potential Agricultural Land Use Types in A Luoi district, Thua Thien Hue province, Central Vietnam

DISSERTATION

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Preface

The present thesis “Soil Properties Mapping and Land Evaluation for Potential Agricultural Land Use Types in A Luoi district, Thua Thien Hue province, Central Vietnam” has been submitted in partial fulfilment of the requirements for the Ph.D. degree at University of Göttingen (Germany). The main supervisor was Prof. Dr. Martin Kappas and the second supervisor was Prof. Dr. Ralph Mitlöhner

The thesis consists of an introduction to the research objectives and questions, a general litter review, a brief of study site’s characteristics, three manuscripts and a summary, limitation and recommendation.

The study was conducted at the Department of Cartography, GIS and Remote Sensing from May 2015 to June 2019.

Göttingen, June 2019

Pham, Gia Tung

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Abbreviations

AL	Arable Land
ALES	Agriculture Land Suitability Evaluator
ANOVA	Analysis of Variance
CI	Consistency Index
CR	Consistency Ratio
DEM	Global Digital Elevation Model
DOS1	Dark Object Subtraction
FAO	Food and Agriculture Organization of the United Nations
FGD	Focus Group Discussion
GIS	Geographic Information Systems
GL	Grassland, Shrub
IDW	Inverse Distance Weighting
ISLE	Intelligent System for Land Evaluation
MCDA	Multi Criteria Decision Analysis
ME	Mean Error
NDVI	Normalized Difference Vegetation Index
NF	Natural Forest for Production
NIR	Near-Infrared
OC	Organic Carbon
OK	Ordinary Kriging
PF	Plantation Forest for Production
pH	Soil Acidity level
PRA	Participatory Rural Appraisal

RI	Random Index
RK	Regression Kriging
RMSE	Root Mean Square Error
RS	Remote Sensing
SOC	Soil Organic Carbon
STN	Soil Total Nitrogen
TOA	Top of Atmosphere Reflectance
US	United State
USGS	United States Geological Survey
USSR	Union of Soviet Socialist Republics
VND	Vietnam Dong

Abstract

Agriculture plays an essential role in Vietnam, especially central Vietnam, which is the least developed economically and socially compared to the other regions. Many administrative levels in Vietnam have implemented “top-down” agricultural land use planning. In this system, the government assigns a specific land use for each given area. However, in the past, they have not paid attention to land evaluation during this process. This shortcoming has often led to irrational agricultural land use. This study was conducted in A Luoi district, Thua Thien Hue Province, Vietnam with the overall objective of mapping soils properties and evaluating land suitability for potential agricultural land use types.

In the first part of this research, the differences among soil organic carbon (SOC), soil total nitrogen (STN), and pH under different land use types and topographic aspects were compared. Soil organic carbon contents in arable land and plantation forest are higher than in natural forest and grassland ($p < 0.05$). Conversely, the soil total nitrogen in natural forest was significantly lower compared to other land use types. The soil of grassland, natural forest, and plantation forest were more acidic than from the arable land use type. Soil organic carbon and soil total nitrogen decreased with increase of soil depth in all land use types. The soil pH in plantation forest and arable land use types showed no significant change in relation to soil depth. Significant differences were also not found between topographic aspect and soil organic carbon content.

The second part of this research consisted of an accuracy comparison between the ordinary kriging (OK) and regression kriging (RK) methods for soil organic carbon, soil total nitrogen, and soil pH (from 117 soil samples). The results show that land use type, transformed soil adjusted vegetation index, and topographic wetness index are not suitable variables in the regression kriging model for soil organic carbon and soil total nitrogen mapping, however land use type could improve the accuracy of soil pH mapping. In general, the OK method seemed more accurate than the RK method for SOC mapping (by 3.33%) and for STN mapping (by 10%), but the RK method was found to more precise for soil pH mapping (by 1.81%).

Finally, the result from the Participatory Rural Appraisal (PRA) method indicated that five crops have good development prospects at the research site, namely rice, cassava, acacia, banana, and rubber. The land suitability for each type of crop is different depending on the weighting of natural conditions, economic aspects, and social aspects. An agricultural land use plan for A Luoi district was proposed based on the land evaluation results. Overall, acacia and cassava are the most suitable land use type at the site. Rubber represents the preferential crop in only a very small patch (5 hectares) in A Luoi Town commune. The parts of the central valley region are the only places in which rubber cultivation would be feasible. Banana cropping is feasible only in small areas in A Luoi Town and the neighboring communes along the main road, totaling 437 ha. The areas in which rice represents the crop of choice is also limited with an extent of 1,388 ha, and are scattered across the northwestern communes of Hong Bac, Bac Son, Hong Trung, Hong Van, and Hong Thuy. With an area of 23,835 hectares, cassava has the highest suitability indices compared to all other land use options. The cassava regions are predominantly located in the remote communes along the western border of the district, as well as in Huong Nguyen and Hong Thuy. The largest contiguous area for cassava production can be found in southern Huong Phong commune. Acacia also has a high suitability with the largest contiguous area, amounting to 18,438 hectares. The preferential acacia region expands from the northern communes along the valley toward the southern and eastern parts of A Luoi district. The combination of scientific and local knowledge in land assessment based on Geographic Information Systems (GIS) technology, Analytical Hierarchy Process (AHP), and PRA method is highly feasible. Systematic integration of PRA and reviews of existing literature is an appropriate land evaluation method.

Chapter 1. Introduction

1.1. General introduction

With a growing population on the world, land productivity is getting pressured to increase, especially with respect to agriculture and forestry land cover [1]. According to Food and Agriculture Organization of the United Nations (FAO) [2], to meet minimum food demand by 2050 there must be a substantial increase (70%) in global food production. Meanwhile, the conversion from reserved to arable land is limited due to the loss of ecology and lack of supporting infrastructure [3]. Land productivity is a combination of the physical nature of the land, climate, management practices, and is limited by these characteristics [4]. In the future, for sustainable development, an increase in global agricultural production is expected to result from further application of new and existing technologies and practices [5]. For future agricultural production, suitable land use planning is therefore required at various scales.

According to FAO [6], land suitability is the fitness of a given type of land for a defined use. McDowell et al. (2018) [7] define land use suitability as a framework for assessing the suitability of land for primary production, accounting for the connections between land use and economic, environmental, social, and cultural impacts. Land suitability is a result of a complicated process, called land evaluation, which is based on many factors that influence land use. Land suitability can be impacted by many factors, such as climate change [8], as well as economic and social factors [9].

The evaluation method is a popular research area in land suitability [10]. Land evaluation documents by FAO (1976, 1984, 1996) [6,11,12] have assessed the methodology of eco-physical conditions with a so-called "top-down process". Sys et al. (1993) [13] introduced detailed requirements of physical conditions for some main crops, however, application of these frameworks in land evaluation at local scales is controversial because of contradictions with local conditions [14]. Elsheikh et al. (2013) [15] introduced a tool called the Agriculture Land Suitability Evaluator (ALES) for land evaluation based on the FAO framework, but this tool only focuses on physical conditions. Hence a "bottom-up" approach [16] and the participation of farmers [17], combined with the FAO framework, should be considered a more sustainable method of land evaluation.

Vietnam is an agricultural country in southeast Asia with a total natural area of 331,051 km^2 [18]. In 2016, Vietnam's population was 95.5 million people, with more than 64% of them residing in rural regions and 42% of the labor force working for agricultural field. While the area of agricultural land has been expanding in recent years, the productivity and value of agricultural production in Vietnam are still lower than in comparison with some countries in the region such as Thailand and China [19]. These issues pose many challenges to agricultural development in Vietnam. In order to solve these problems, it is necessary to have a plan for sustainable agricultural land use, in which land evaluation is an essential and indispensable part.

Among the three macro regions of Vietnam, the central region is the least developed [20]. No land evaluation studies have been carried out in this area concerning physical, economic, and social criteria based on scientific and local knowledge, however, Huynh (2018) [14] conducted research about land evaluation at the commune scale, but his study was conducted in only a small area with a high homogeneity of eco-social criteria.

1.2. Research objectives

The goal of this research is to combine the scientific and local knowledge for land evaluation to determine potential agricultural land use types.

Specific Objectives:

a) Determine the potential agricultural land use types for A Luoi district in the future.
b) Determine a suitable method for soil properties mapping.
c) Determine the impact of land use on land quality.
d) Determine the land suitability of specific crops for natural, economic, and social conditions.

1.3. Research questions

This research seeks to address the following questions:

a) What are the potential agricultural land use types in the study area?

b) How does the land use type influence soil quality?

c) What are the characteristics of each land map unit in the study area?

d) Which method is suitable for soil quality mapping in the study area?

e) How suitable is each land map unit for each potential agricultural land use type in the study area?

1.4. Overview of the thesis

This section provides an overview of the content of each chapter. This dissertation is a cumulative version and divided into 6 chapters, of which chapters 3, 4, and 5 have been written in the scientific manuscript structure.

Chapter 1: This chapter presents a basic background of the research proposal development. A brief introduction of the research problems, objectives, and research questions are put forward. The main concept, literature, and methodologies are also introduced.

Chapter 2: This chapter introduces information about the study area, including location, geographical characteristics, soil resources, agricultural production, land use, and other social and economic conditions.

Chapter 3: This chapter presents and discusses soil quality and its relationship to different land use types, as well as different aspects of each agricultural land use type, at the research site. Soil organic carbon (SOC) contents in arable land and plantation forest are higher than in natural forest and grassland ($p < 0.05$). Conversely, soil total nitrogen (STN) quantities in natural forest is significantly less in comparison to other land use types. Meanwhile, there were no significant differences in STN content ($p < 0.05$) among arable land, plantation forest, and grassland. The soils of the grassland, natural forest, and plantation forest land use types were more acidic than the soils of the arable land use type. SOC and STN decreased with soil depth for all land use types. The soil pH in plantation forest and arable land showed no significant change with soil depth. No significant differences were found between topographic aspect and SOC content.

Chapter 4: This chapter presents and discusses soil quality mapping with the ordinary kriging and regression kriging techniques. The results show that the land use type (LUT) variable is more effective than the topographic wetness index (TWI) and the transformed soil adjusted vegetation index (TSAVI) for determining STN and soil pH when using the regression kriging method. In contrast, a combination of the LUT and TWI variables is the best combination for SOC mapping with the regression kriging method, with a variance of 14.98%. The ordinary kriging method was more accurate than the regression kriging method for SOC mapping (by 3.33%) and for STN mapping (by 10%), but the regression kriging method was found to be more precise for soil pH mapping (by 1.81%).

Chapter 5: This chapter discusses land evaluation based on the integration of local and literature knowledge via the participatory rural appraisal (PRA) method. The results of the PRA method indicated that five crops have potential development prospects at the research site, namely rice, cassava, acacia, banana, and rubber. The land suitability for each kind of crop is different depending on the weighting of natural, economic, and social aspects. Acacia and cassava are the most suitable land use type in the research area as a whole. A recommendation for agricultural land use planning in A Luoi district was proposed based on the land evaluation results. The combination of scientific knowledge and local knowledge in land assessment based on Geographical Information Systems (GIS) technology, Analytical Hierarchy Process (AHP), and PRA method is highly feasible. The systematic integration of PRA and review of existing literature is an appropriate method for land evaluation.

Chapter 6: This chapter summarizes findings and states contributions, limitations, and recommendations for future work.

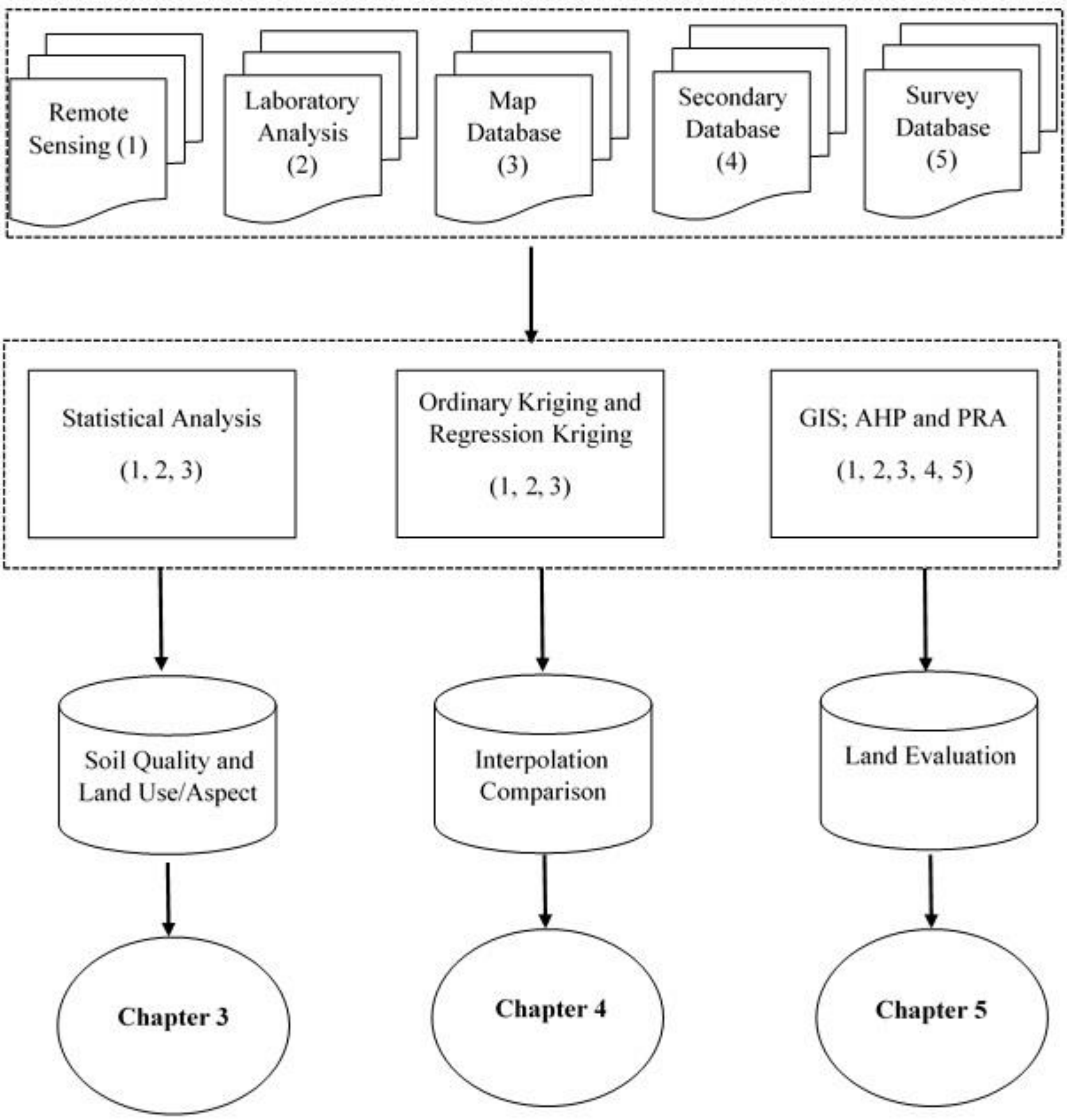

Figure 1.1. Overview of research concept

1.5. Concept, literature review and methodologies

1.5.1. Soil quality and soil mapping

Soil quality is the ability of soil to provide nutrients to plants, maintain water and air within the soil, and support human needs [21]. Chemical, biological, and physical indicators usually define soil quality, depending on particular constituents, processes, or conditions [22]. Many factors influence soil quality (e.g. topographic aspect, climatic conditions, land use type)

[23–26], which is an essential criterion for land evaluation [27,28]. Soil pH, soil organic carbon, and soil depth are usually used for land evaluation [29].

According to FAO classification, Vietnamese soils are classified into 13 main soil groups [30], of which Acrisols are the dominant soil (covering about 50% of the land), followed by Gleysols (13%), Fluvisols (8%), Cambisols (7%), Ferralsols (5%) and Luvison (2.5%). For agricultural purposes, the content of soil organic carbon in soil fluctuates from 0.68% to 3.8% of soil weight. Meanwhile, soil pH ranges from 3.54 to 5.74, and soil total nitrogen fluctuates between 0.05% and 0.25% of soil weight. More than 36% of agricultural soil has low inherent nutrient supplying capacity, low organic matter, and limited water holding capacity [31]. In general, more than half of the country's arable land is of poor quality and needs improvement [32].

Soil mapping is a result of field surveying, laboratory analysis, and interpolation techniques. A soil map is a graphic representation of the spatial distribution of soil attributes [33]. The development of certain techniques, such as GIS or remote sensing, leads to more effective and data rich soils maps compared to the traditional method [34]. Digital soil mapping is defined as the creation and population of a spatial soil information system by using field and laboratory observational methods coupled with spatial and non-spatial soil inference systems [35]. Digital soil mapping is an essential part of the soil assessment framework and support soil related decision making [36]. Many methods are used to monitor the spatial distribution of soil quality indicators through GIS technologies [37–40].

Until 1975, two soil map systems co-existed in Vietnam. In the northern part (north of the 17th parallel), soil classification followed the Union of Soviet Socialist Republics (USSR), meanwhile the southern part utilized the United States (US) classification [30]. Based on the soil map of the world on a 1:5 million scale (completed by FAO – UNESCO) in 1976, a soil map of Vietnam was created following the FAO legend on a 1:1 million scale [30]. In 1979, some regions developed soil maps to serve agricultural development in northern Vietnam, followed by soil maps for the provinces of Dak Lak, Kon Tum and Gia Lai in 1999 [41]. Some other small regions also invested in soil mapping to serve specific missions in the agricultural field [42,43]. These maps, however, show only basic information such as soil type, terrain, and soil depth.

1.5.2. Land use and land use planning

Land use is the term used to describe the human use of land. Land use refers to the difference in economic activities in a given area and the human behavior patterns they create, as well as their effects on the environment [44]. In contrast, FAO defines land use as "the arrangements, activities and inputs people undertake in certain land cover types to produce, change or maintain it" [45]. Many factors determine land use, including natural physical conditions, cultural context, political aspects, and economic dynamics [46,47]. In Vietnam, a land law was passed by the Vietnamese National Assembly in 2013 and took effect on July 1, 2014 (called Land Law 2013), which divided land use into three groups: agricultural land, non-agricultural land, and unused land [48].

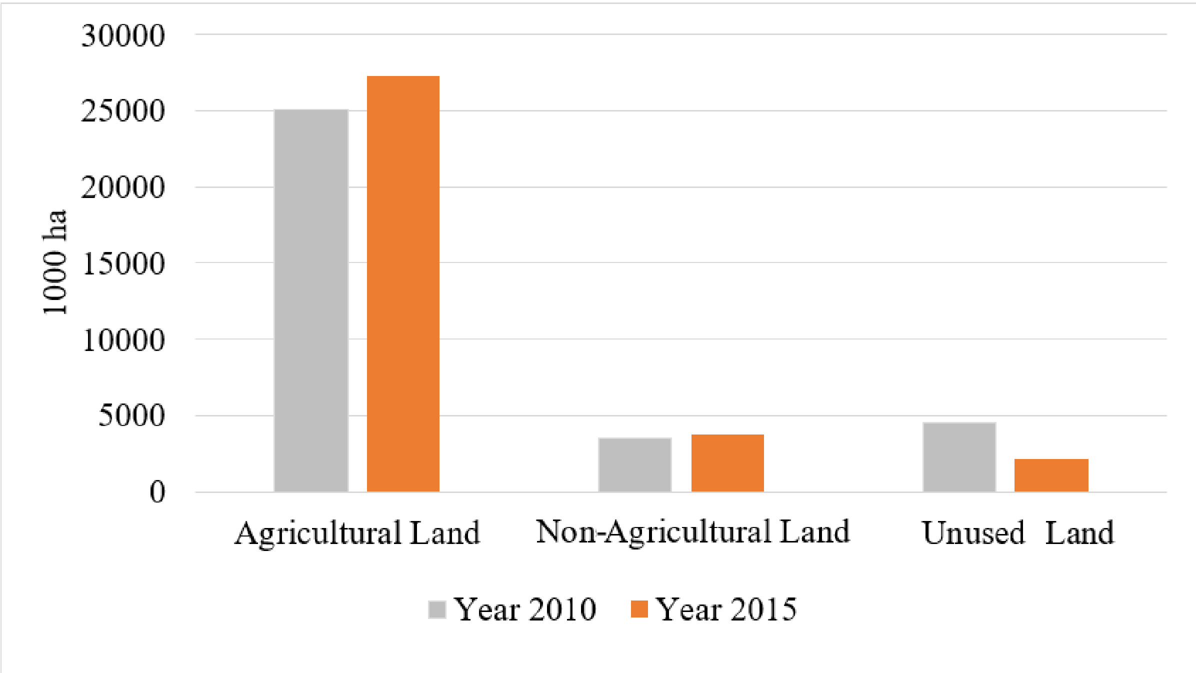

Figure 1.2. Land use types of Vietnam in 2010 and 2015 [49]

The main trend for land use change in Vietnam is that the area for agricultural (including forestry) land use purposes increased, while the unused land area reduced. It is a result of many forestry projects of greening the barren hills in Vietnam. There are many land use types belonging to the agricultural land use category such as forest, yearly crops, aquaculture, and perennials trees.

In 1993, FAO published an internationally recognized definition for land use planning, stating, "Land-use planning is the systematic assessment of land and water potential, alternatives for land use and economic and social conditions in order to select and adopt the best land-use options. Its purpose is to select and put into practice those land uses that will best meet the needs of the people while safeguarding resources for the future. The driving force in planning is the need for change, the need for improved management or the need for a quite different pattern of land use dictated by changing circumstances" [50]. Even though, in 1993, FAO introduced framework with ten steps for land use planning implementation [51], land use planning is flexible and adaptive and may differ substantially when applied at different scales [50,52].

Vietnam's Land Law 2013 stipulates that land use planning must be implemented every ten years at all administrative levels [48]. The implementation of this law is mainly to distribute the area of land resources based on the intended land use purpose, meaning that the process does not consider economic and social aspects or land quality. This implementation is a "top-down process," since lower level plans must be based on the plans of the higher levels [48]. The participation of local farmers could improve the feasibility of land use planning [53], so that all involved parties are satisfied. As in other countries [54], there is usually a years-long time gap between creation and implementation of a land use plan. By the time implementation starts, the foundational data has mostly likely changed, which can cause failure. According to Land Law 2013, land evaluations are not mandatory inputs for the land use planning process, leading to inefficient land use, especially for the agricultural land use type.

1.5.3. Land evaluation

The first FAO publication relevant to the concept and methodology of land evaluation for a given area was published in 1976 [6]. Later versions [12,11,55,56] provided the framework to evaluate land capacity for specific major land uses. FAO (1976) [6] defined land evaluation as "the assessment of land performance when used for a specified purpose, involving the execution and interpretation of surveys and studies of land forms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising kinds of land use in terms applicable to the objectives of the evaluation”. Others [57] have simpler land evaluation concepts through the use of scientific tools to match land characteristics with certain land uses. Beek (1978) [58] proposed that land evaluation predicts the inputs, outputs, and other favorable or adverse effects of a specified land use. In conclusion, land evaluation is the process of determining the suitability of land resources, including physical, economic and social aspects, for specific land use types.

Land evaluation provides a rational basis for land use planning [59], especially in developing countries where there is a need for more arable land to adapt to food demands while simultaneously facing the many negative effects of land degradation and environmental issues [60]. Land evaluation plays an essential role in detecting the environmental limit in sustainable land use planning [61].

In 1976, the FAO proposed a framework for land evaluation with two approaches. The “two-stage" approach consisted of a qualitative land classification followed by an economic and social analysis along with a quantitative land classification. The second, “parallel” approach involved conducting these stages concurrently [6]. Most applications of these approaches, however, have concentrated on assessing only the physical potential of the land [60], and both are top-down approaches without any role for stakeholders. To address this oversight, the FAO issued a revised land evaluation framework in 2007 [29]. In this version, stakeholders are involved from the beginning in all steps related to land evaluation, as it requires information from many different domains (e.g. soil, climate, crop, and management) [59,57].

Many methods have been applied for land evaluation. The US Department of Agriculture proposed a method, called the Land Capability Classification, where they divided soils into eight levels from very little limitations to no value for agriculture [62]. For agro-ecological zones, FAO (1996) [12] introduced a method with three main steps: create an inventory of land use types, land resources, and land suitabilities. The criteria for land evaluation are increasingly quantified [63]. Some studies provide land evaluation computer systems based on the FAO framework, such as the Agriculture Land Suitability Evaluator (ALSE) and the Intelligent System for Land Evaluation (ISLE), but they are still limited by the number of considered factors or only focus to natural conditions criteria [15]. In recent years, many authors have combined Geographical Information Systems (GIS) and Multi Criteria Decision Analysis (MCDA) to implement land evaluation for many specific purposes [64,65].

Sys et al. (1993) [66] provided reference values for physical crop requirements for fifty crop types commonly cultivated in the tropical and sub-tropical regions. These values have been applied by many researchers as a suitable approach for land evaluation [67–71]. However, the requirements provided by Sys et al. (1993) [66] are not detailed enough for smaller areas with specific characteristics

The land evaluation method by FAO has been applied for land resources evaluation by many researchers in Vietnam [72,73]. These studies provided initial achievements, however, they focused too much on physical conditions (e.g. soil type, climatic condition), and too little on socio-economic conditions [14]. Land evaluation usually follows the FAO framework and is often conducted with a top-down approach in big ecological zones. As a result, many findings of land evaluation in Vietnam are difficult to apply in practice. In recent years, some researchers have become interested in smaller scale zones (i.e. district or commune levels) [74,75]. These studies only focused on selected land use types, so the participation of land users during the land assessment process was incomplete.

1.5.4. Methodologies in an overview

1.5.4.1. Soil sampling and soil quality analysis

Soil sampling plays an indispensable role in soil quality assessment. The common approach, grid sampling, is to overlay a square or rectangular grid on a map of the area to be sampled, identify the location of each grid cell center, and collect a soil sample from that point [76]. Grid sampling is a good method, but it requires a sufficiently dense grid and is very expensive. In order to decrease the cost and time involved with this method, we conducted directed sampling by using auxiliary information in addition to a grid [77]. Soil samples were collected based on grid soil sampling and soil units. Soil units were determined by overlapping a soil type map, land use map, and slope map. The grid size was 2 km x 2 km in general cases and 4 km x 4 km for areas of highly homogeneous soil unit characteristics. All soil samples were air dried and passed through a 2 mm sieve for further analysis.

Figure 1.3. Soil sampling in the field

In total, 155 soil samples from the soil layers between 0 and 30 cm and between 30 and 60 cm were collected from 78 soil map units with grid sampling. The soil samples were then analyzed to determine SOC, STN, and pH. All samples were analyzed at the Laboratory of the Soil Science Department of Hue University of Agriculture and Forestry, Vietnam. SOC was determined by the Walkley-Black method [78], STN was determined by Kjeldahl´s digestion [79], and pH was measured using a portable pH meter with KCl 1 M [80].

In this research, the values of soil quality indicators at two layers were used for analysis of the relationship between soil quality and land use type (Chapter 3), while the values of the topsoil layer were used for research on soil quality mapping techniques (Chapter 4). An averaged value of soil qualities for both soil layers was used for land evaluation (Chapter 5).

Figure 1.4. Soil samples and soil analysis at the laboratory

1.5.4.2. Statistical analysis

An analysis of variance (ANOVA) and the post hoc multiple comparisons test were used to evaluate the differences in soil quality indicators between land use types. A paired samples test was used to assess the differences of soil indicators between both soil layers (Chapter 3). Some indexes (e.g. mean, median, skewness, kurtosis, and root mean square error) were used to describe the data (Chapter 3, 4, 5).

1.5.4.3. Participatory rural appraisal (PRA)

The PRA method facilitates collecting the opinion of farmers and other key actors in agricultural and rural research [81]. A part of this method, the Focus Group Discussion (FGD) is a qualitative research method and data collection technique in which a selected group of people discusses a given topic [82]. Our study used the FGD method mainly for the land evaluation section (Chapter 5). In general, we conducted three FGDs for each of the following topics: crop selection (5 groups, 3-5 participants per group), economic criteria evaluation (6 groups, 5 participants per group), and social criteria evaluation (1 group, 4 participants). We also conducted private interviews with experts in soil science and crop science for physical criteria evaluation. In total, 30 participants responded to our questionnaires, twenty-one local experts, and nine international researchers. For each discussion, the GIS participatory tool was used to determine the result of the criteria (for economic and social criteria) on the map.

Figure 1.5. Group discussion with the local peoples

1.5.4.4. Geographical information systems and remote sensing

GIS and Remote Sensing (RS) plays an indispensable role in this study. Many input data were extracted from RS resources such as slope and elevation maps. The research also used map data from different formats and coordinate systems. All maps were created, analyzed, and stored in the ArcGIS software format. Two types of GIS data were used in this study (i.e. spatial databases and attribute data). The details of both the GIS and RS methods are described in each chapter of this thesis.

1.5.4.5. Multi criteria decision analysis (MCDA)

Land evaluation is a process that involves a large number of attributes and different criteria for decision making, and therefore land evaluation can be viewed as a multi-criteria decision analysis (MCDA) process [83]. The Analytical Hierarchy Process (AHP) method developed by Thomas L. Saaty (1987) [84] is a MCDA approach that is frequently used in GIS-based land use planning [85–89]. The AHP is a method for deriving a priority scale through pairwise comparison of attributes based on expert judgements [90]. The procedure of the AHP method was implemented sequentially following three main steps: set up a hierarchy structure model, create a judgment matrix according to the relative importance of each criteria, and check the consistency of the final matrix of judgments. A detailed description of this method is presented in Chapter 5.

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Chapter 2. Overview of research area

2.1. Location

Vietnam is located in southeast Asia with a mainland area of approximately 33 million hectares [1]. The mainland is located from $8^0$30’0’’N (in Ca Mau Province) to $23^0$22’0’’N (in Ha Giang Province) and from $102^0$10’0’’W (in Lai Chau province) to $109^0$24’0’’E (in Khanh Hoa Province). Mountains and hills account for 75% of the mainland, most of which is less than 1000 m above sea level. The plains area is a narrow strip that runs along the country, which then expands at the north end (Red River Delta) and south end (Mekong River Delta).

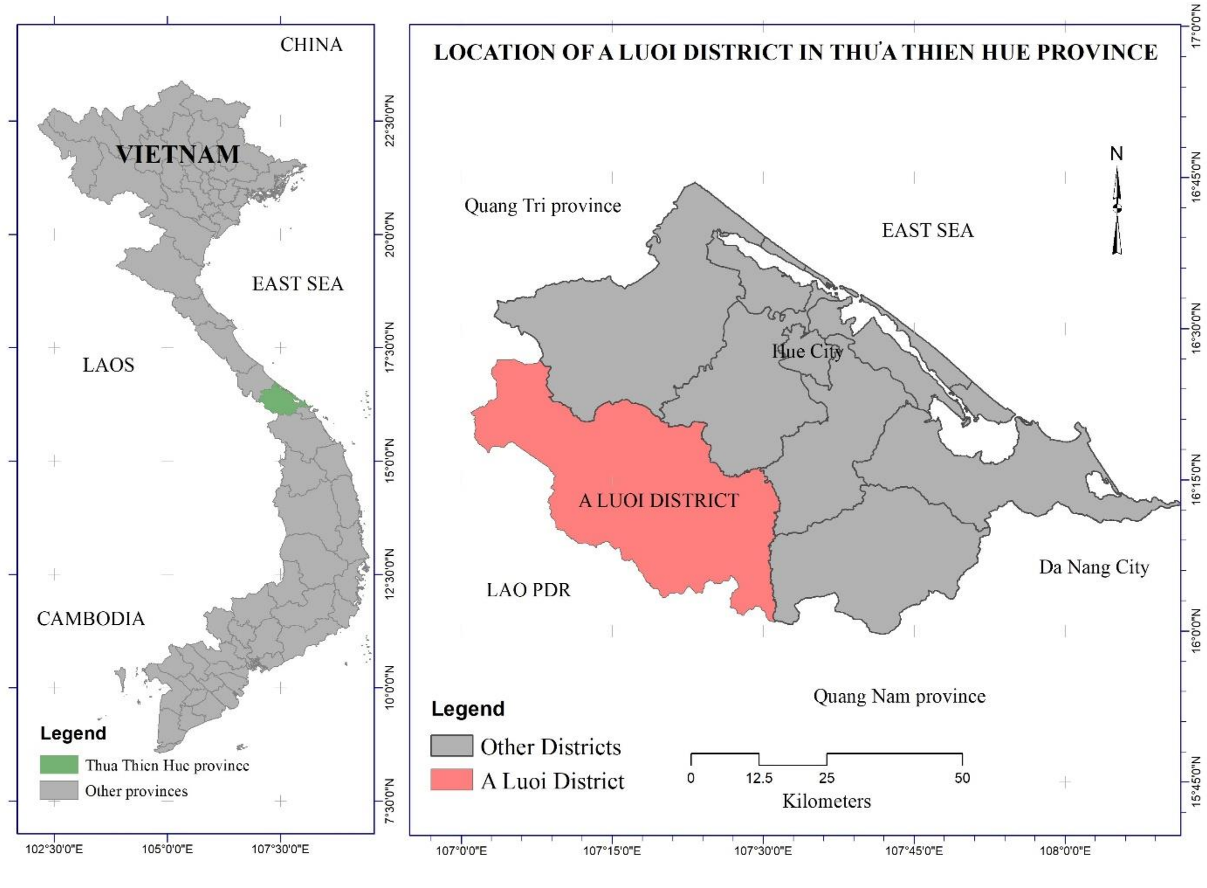

Figure 2.1. Location of Thua Thien Hue province and A Luoi district.

This study focuses on the hilly regions in Central Vietnam. The agricultural land use type of A Luoi district was chosen as the research area, which is located between 107°E and 107°30´E, and 16°N and 16°30´N, approximately 60 km west of Hue city, in Central Vietnam (Figure 2.1). The A Luoi district has mountainous and hilly topography, with ranges of heights between 35 m and 1814 m above sea level, decreasing from west to east. The slope of the terrain is complex and steep, a majority being between 10 and 30 degrees (Figure 2.2 and Table 2.1) [2,3].

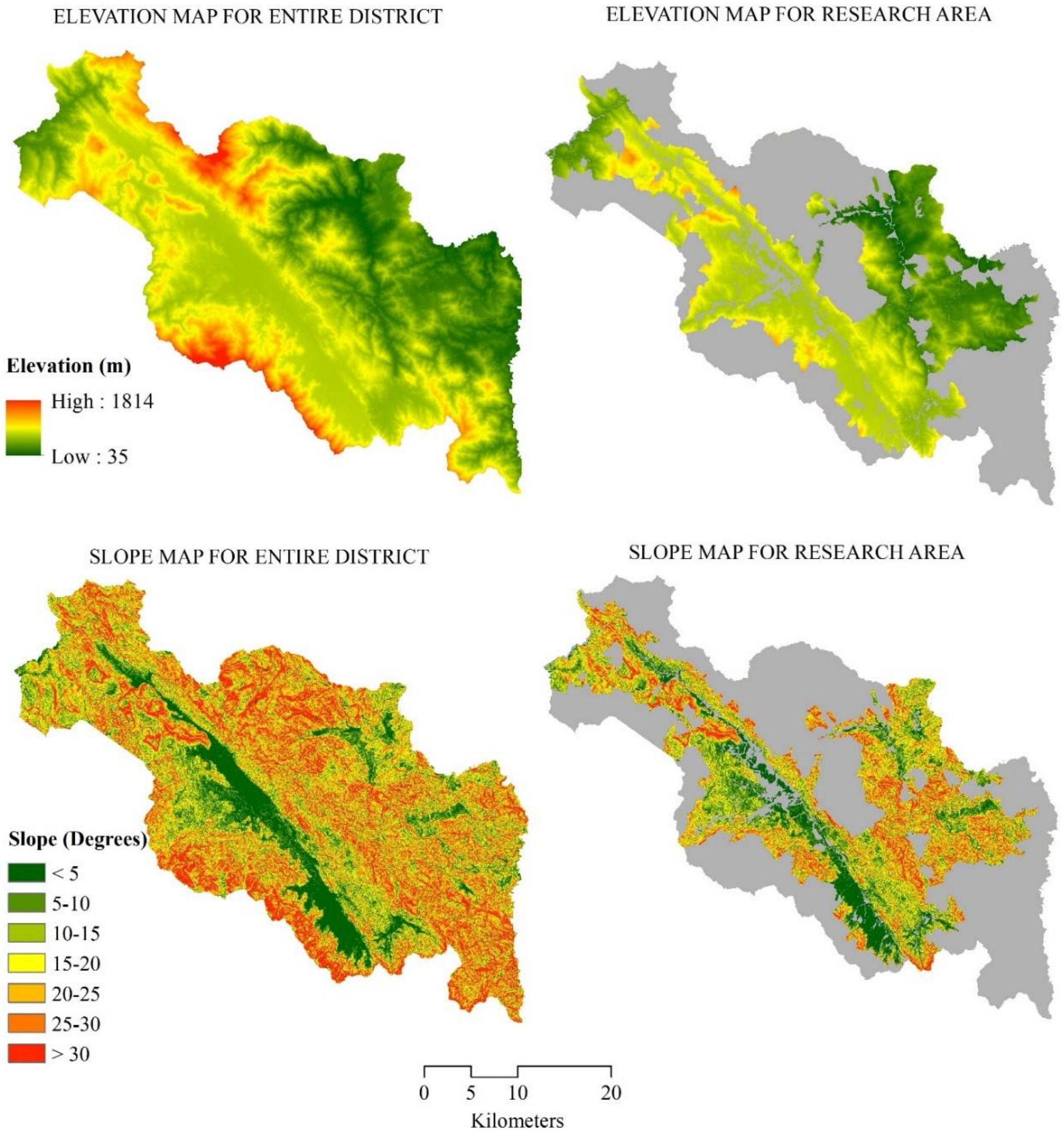

Figure 2.2. Terrain and slope of A Luoi district (left) and research area (right).

2.2. Climate

The climate at the research site exhibits tropical monsoon characteristics. Annual precipitation of A Luoi district from 2005 to 2017 was nearly 3500 mm. The rainy season from September to December accounts for 70% of total annual precipitation. A Luoi district receives slightly more precipitation than the entire Thua Thien Hue Province. In contrast, the average temperature of A Luoi district is significantly lower than the entire province by around 2°C.

The average temperature is the highest in May and lowest in January at 25°C and 17°C, respectively (Figure 2.3) [4].

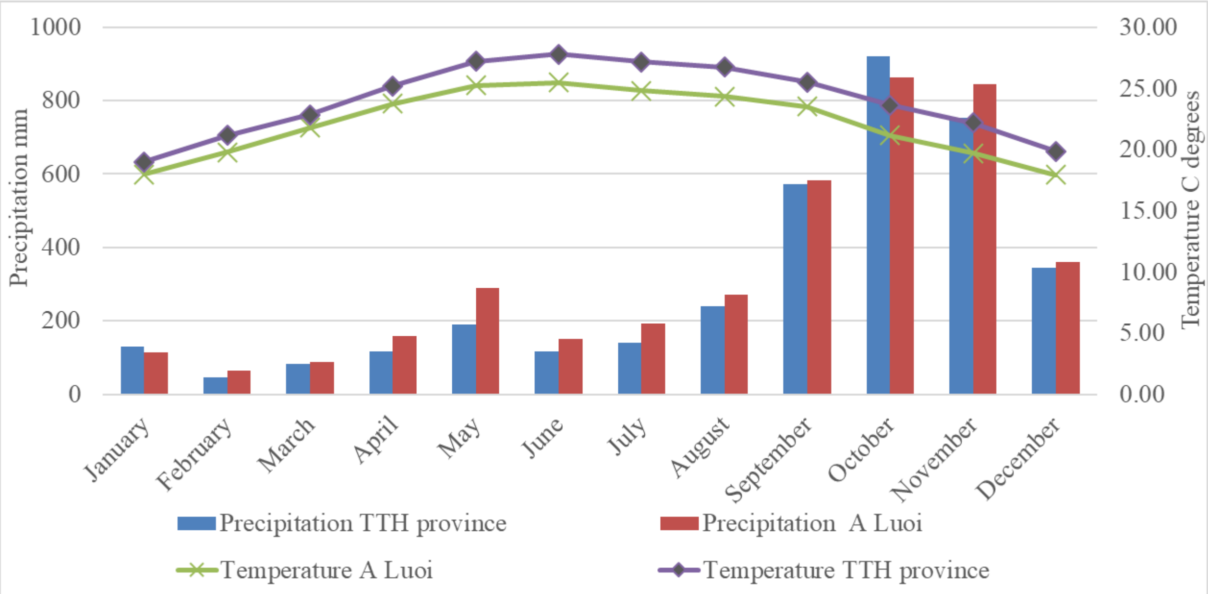

Figure 2.3. Monthly precipitation and temperature of A Luoi district (2005-2017).

2.3. Soil resources

The primary information about soil type, soil depth, and soil texture was extracted from the Thua Thien Hue Province soil map at a scale of 1/100,000 [5]. Based on the international classification system [6], there are four soil types within A Luoi district: Acrisols (ferralic) (covering 75% of the land), Acrisols (arenic) (14%), Acrisols (humic) (6%), and Acrisols (hyperdystric) (5%). The Acrisols (ferralic) are located throughout the district, while Acrisols (arenic) can be found in the central eastern parts of the district as well as in smaller parts of the central northern part. The Acrisols (hyperdystric) are situated exclusively in the northwest-southeast oriented valley that bisects the district. Acrisols (humic) are present in small patches, mainly in the northwest of A Luoi.

Soil depth plays an essential role in land use for agricultural purposes. It affects the development of roots and facilitates the water and nutrition absorption process [7,8]. The soil depth of A Luoi district ranks with five levels, of which soil with a layer depth of more than 100 cm is the most substantial. The soil depth of less than 30 cm has the smallest area. The diversity of soil depth is an advantage for developing different kinds of crops.

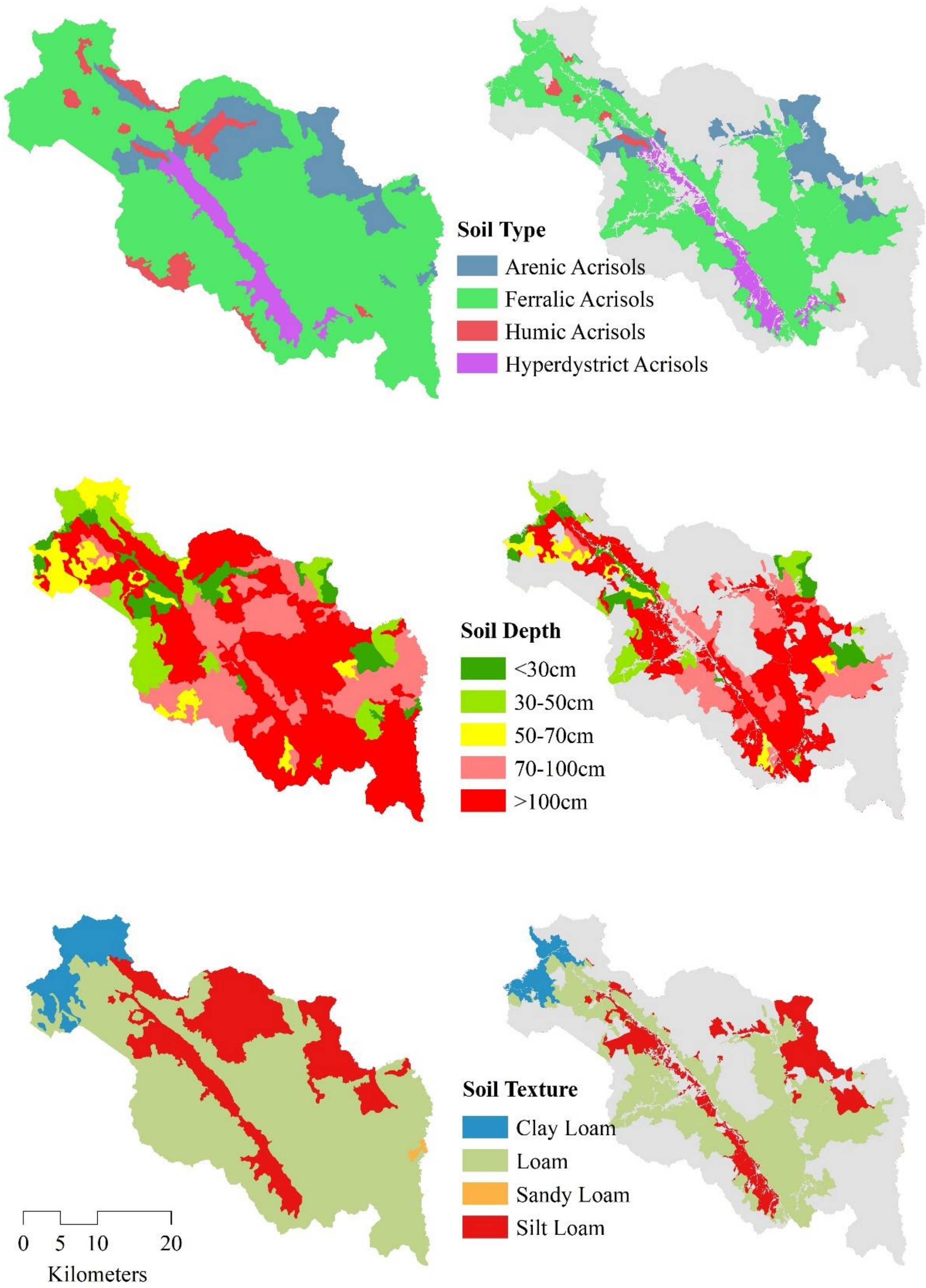

Figure 2.4. Soil type, depth and texture of entire district (left) and research area (right).

Table 2.1. Soil characteristic of entire district and research area

	Entire district (ha)	Research area (ha)
Elevation (m)		
< 500	41,780	21,282
501 – 750	50,350	28,761
751 – 1000	20,179	5,845
> 1000	10,104	466
Slope		
< 7.9	20,249	12,943
8 – 14.9	23,899	18,451
15 – 25	42,415	17,289
> 25	35,747	7,672
Soil type		
Acrisols (arenic)	16,630	8,566
Acrisols (ferralic)	92,232	42,800
Acrisols (humic)	6,928	985
Acrisols (hyperdystric)	6,637	4,004
Soil depth (cm)		
< 30	8,262	4,886
30 – 49	14,327	4,906
50 – 69	9,275	3,329
70 – 100	29,260	14,469
> 100	61,357	28,764
Soil texture		
Clay loam	8,595	3,453
Loam	84,621	39,739
Sandy loam	296	0
Silt loam	28,913	13,162

Soil texture is one of the most stable soil properties and therefore a useful index for several other properties that determine the agricultural potential of the soil. It has the most impact on moisture retention [9]. For example, clay soil has moisture holding capacity; but in heavy rainfall regions, it would be difficult for farming. In this study, soil texture is divided into four groups. The loam soil occupies the most significant area with around 70% of entire district, meanwhile the sandy loam soil accounts for a miniscule percentage (Figure 2.3 and Table 2.1).

The results of the analysis for the 155 soil samples and the spatial interpolation show that the percent of SOC content of the average of both soil layers ranges from 0.67 to 1.55%. The SOC of the research area is low compared to average levels from a SOC classification for all of Vietnam [10].

The STN amount varies from 0.058% to 0.123%. The average quality of STN in the agricultural land of A Luoi belongs to the medium level group according to the classification table of STN content for Vietnamese soil [10]. The lowest nitrogen levels can be found in the central eastern region of the district while higher values can be measured in the central western part, in the valley, and in the southern part of the potential agricultural area.

The soils for agricultural purposes in A Luoi district have a pH ranging from 3.9 to 4.4 for the mixture of both soil layers. The lowest pH values can be found in the northern part of the district along the border as well as in a small area of the central valley.

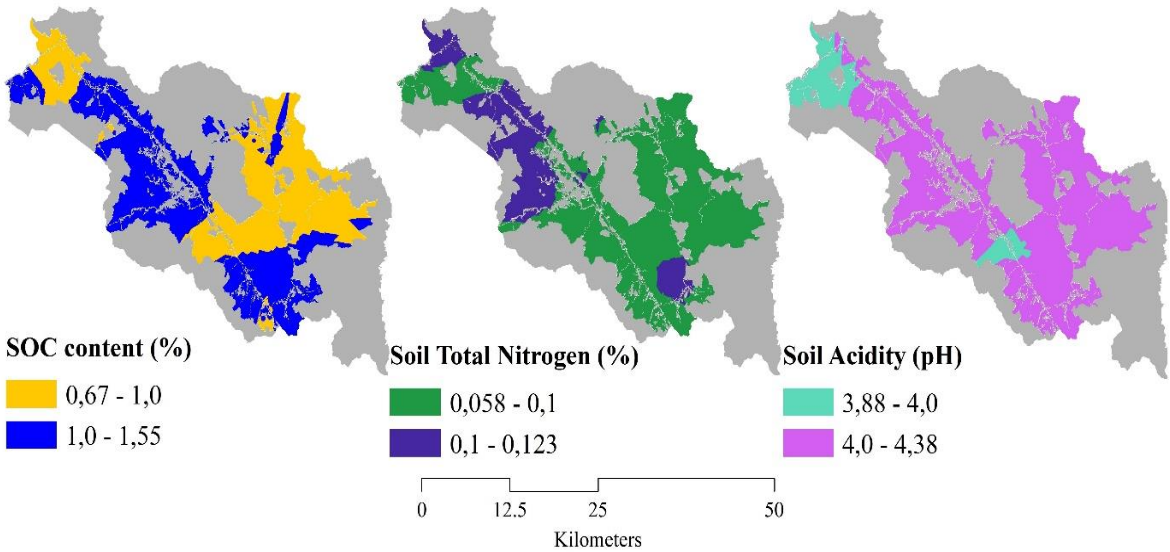

Figure 2.5. Soil quality indicators of research area.

In general, the soil resources of the research area are diverse, creating the needed conditions to cultivate many agricultural land use types. All sustainable approaches to land use have a requirement to reduce soil degradation. In the long term, much more financing and time is needed to improve the SOC, STN and reduce the negative influence of soil acidity on agricultural production.

2.4. Land use

According to statistical data [4] and surveys during 2017, agricultural land occupied 92% of the total area, followed by unused land and non-agricultural land with 4% for both of these land use types (Figure 2.6).

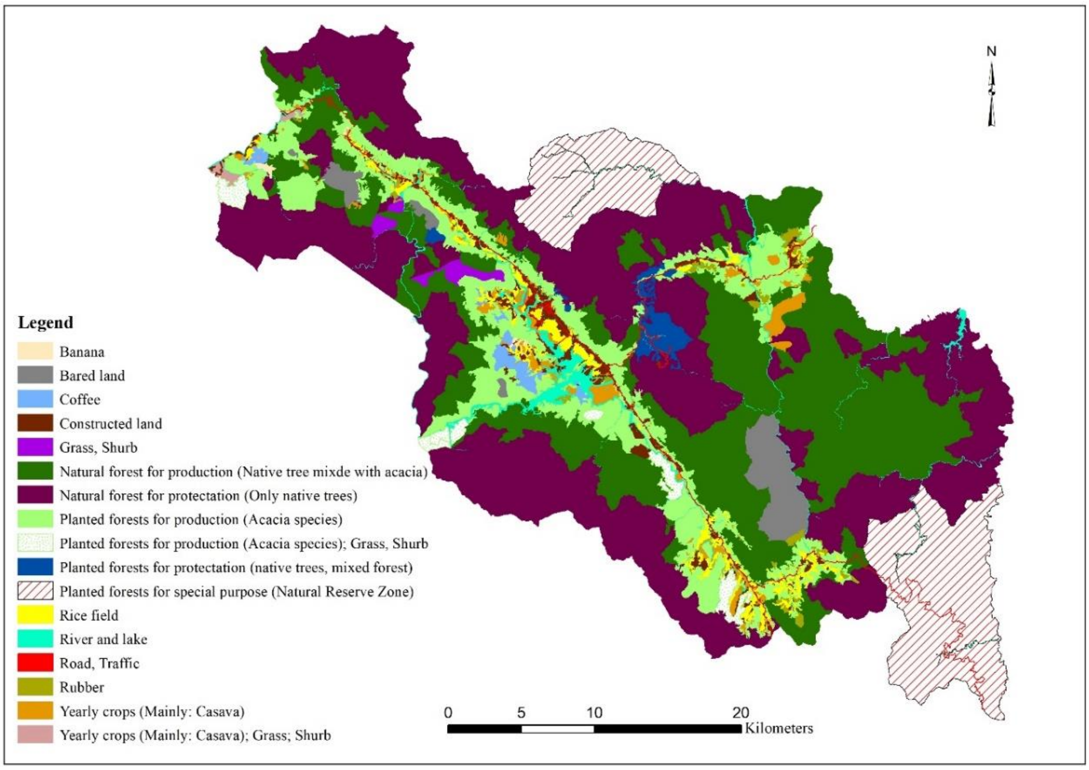

Figure 2.6. Land use map in 2015, updated in 2017

The following land is available for production (the agricultural land use type): 32,653 ha of natural forests (NF) for production, 15,804 ha of plantation forests (PF), 5,252 ha of grasslands (GL), and 3,783 ha of arable lands (AL). However, there is 44,746 ha of forest for protection and 15,359 ha of forest for special purposes is not available for agricultural production [11].

Forest for special purposes is used for nature conservation, as a source of specimens of the national forest ecosystem and forest biological genes, for scientific research, protection of historical and cultural relics, landscape protection, in service of recreation and tourism, and environmental protection. Protection forests are used mainly to protect water sources and land, prevent erosion and desertification, restrict natural calamities, and regulate climate, thus contributing to environmental protection [12].

Article 58 of the Vietnamese Land Law 2013 [12] states that protection forest land or forest for special purposes can be transferred to other land use purposes only with approval from the Prime Minister. Transferal is a very complicated process and requires many procedures. Moreover, the shifting from forestland to other lands is practically impossible, since Vietnam is attempting to keep and increase the forest area. Therefore, these kinds of land use types are not included in our research area regardless of whether they belong to the agricultural land use type.

Eight main land use types belong to the agricultural category in the research area:

1. Planted production forest (acacia), 14,195 ha: This land use type is prevalent in central Vietnam and in particular, A Luoi district. This land use type is usually located in areas close to residential areas or terrain that is not too steep. Usually, farmers plant in the spring season (March, April) and harvest after 3–4 years. This land use type is being expanded because it is suitable to the farming skills of the local people and the market for product consumption is stable, enabling the local people to earn an acceptable income.

2. Banana and acacia, 132 ha: This is a crop rotation between banana and acacia of which banana plays a significant role. The land users plant banana in two consecutive cycles (about 2–3 years) and then plant a cycle of acacia (about 3–4 years). As explained by local people, they want to supply the acacia trees with the residual nutrients in the soil that remains from the banana growing.

3. Bare land, 5,253 ha. This area belongs to government management and it is not allocated for any land users. The presence of crops in this area is relatively few, and most of them are grass or shrubs.

4. Cassava, 2,005 ha: Cassava is one of the most popular crops of A Luoi district. This kind of crop is usually planted on low hills and around residential locations. The growing season

of cassava is from June to December every year. In general, the local people have experience with cassava cultivation and it does not require much farming skill, finance, or time.

5. Coffee and acacia, 738 ha: This area is located in Nham commune, in the center of the district. Ten years ago, several agricultural projects supported coffee planting in A Luoi district. As a supported policy, the government will provide free fertilizer for farmers who plant coffee. However, these projects have failed because the coffee plant is not suitable for the natural conditions of A Luoi district and the farming skill of local people is not suited to coffee planting. Gradually, people planted acacia trees in coffee growing areas. They still own (but do not maintain and nor harvest) existing coffee areas in order to continue receiving fertilizer from the government. In the future, when the fertilizer support program ends (in 2020), this area will likely be converted to acacia plantations.

6. Natural production forest, 32,653 hectares: Natural forest is forest that already exists and was not grown or planted by humans. Land users have the right to plant additional kinds of trees (most of them being acacia) and to benefit from these planted trees, as well as benefit from non-timber products from the natural forest. To exploit the products from the natural forest for productions, the land users need a detailed plan that must be accepted by the local authority. This kind of forest is located in steep areas, quite far from residential locations.

7. Rice, 1,778 hectares: This type of land use is distributed in areas with flat terrain and available water resources. Rice cultivation is scattered in small areas that are interspersed among residential areas. The rice product is used only for household demand.

8. Rubber and acacia, 738 hectares: The acacia is intercropped between two rows of rubber within the first 3-4 years when young rubber is growing. This is so that acacia can take advantage of the fertilizer used for the rubber trees. Income from acacia will support the rubber growing process because, early in the process, rubber trees do not provide any economic benefits. In addition, acacia trees provide a barrier for rubber trees, protecting them from other falling trees during the stormy season.

Figure 2.7. Some of land use types in A Luoi

2.5. Population and income

According to the district's statistics in 2017, there were 21 communes in A Luoi with 110 villages. The population of A Luoi is 49,466 inhabitants; with a density is 40 people per square kilometer. Most of the population is concentrated in the center of the district, where it is flat and along a national roadway. The natural population growth rate ranges from 15.5‰ (in 2013) to 16.7‰ (in 2017). People of working age account for 50% of the population. There are four ethnic groups in A Luoi district: the Ta Oi, Co Tu, Van Kieu, and Pa Ko. They account for more than 75% of the total population [4] (Table 2.2.)

Table 2.2. Population and poverty rate of communes in A Luoi district in 2017.

	Area (km^2)	Population (Person)	Density (Person/km^2)	No. of households	Poverty rate (%)
Total	*1,225.21*	*49,466*	*40.38*	*12,405*	*37.40*
A Luoi town	14.17	7,493	528.79	2030	9.81
A Roang	57.88	2,732	47.20	610	49.26
A Dot	16.58	2,422	146.80	579	45.41
Huong Lam	51.28	2,210	43.10	530	40.95
Huong Phong	81.16	508	6.26	190	1.07
Hong Thuong	40.32	2,747	68.13	715	27.97
Hong Thai	69.27	1,114	16.08	290	65.52
Hong Quang	5.39	2,206	409.28	565	46.00
A Ngo	8.76	3,449	393.72	830	8.35
Son Thuy	16.73	2,926	174.90	751	7.06
Phu Vinh	28.13	1,080	38.39	330	7.69
Hong Kim	40.89	1,990	48.67	515	50.40
Hong Bac	31.19	2,182	69.96	510	35.04
Hong Van	43.92	3,104	70.67	780	56.47
Hong Trung	67.40	2,082	30.89	530	63.02
Bac Son	10.34	1,227	118.67	300	44.15
Hong Thuy	112.80	3,135	27.79	750	37.57
Dong Son	26.70	1,464	54.83	350	47.43
Huong Nguyen	323.98	1,326	4.09	310	58.06
Hong Ha	140.47	1,760	12.53	415	31.33
Nham	37.85	2,309	61.00	525	52.95

Agriculture accounts for 80% of local people's income. According to statistics and field survey in 2017, the annual income of the local people is 14 million VND (approximately 520 euro/year) [4]. In Vietnam, poor people are defined as those who earn up to VND 700,000 (26 euro) a month in rural areas. The poverty rate of A Luoi district is very high, at about 37% of households [4] (Table 2.2). The poverty rate of the communes located in the center of the district is lower in comparison to other communes because of the advantages provided by infrastructure and access to information. More than 75% of the labor force works for the agricultural sector, even though most are not trained in the basic skills related to agricultural production.

Figure 2.8. Local people in a traditional festival.

2.6. Agricultural production

Agricultural production is the main activity of the local people. In A Luoi district, the five main crops are acacia, rice, rubber, cassava, and banana. There are several other crops such as corn, peanuts, and vegetables, but they occupy a tiny area and do not have an essential role in the livelihood of the local people. The data from the annual statistics of 2017 and our own field trip about agricultural production is presented in Table 2.3.

According to the annual statistics of 2017 [4], acacia planting is the main forest activity of the local people. The planted area has been expanding, and this trend will likely be maintained in the future. The result of the survey in the field indicates that acacia is planted by more than 90% of agricultural households with an average area of one to two hectares per household. Moreover, this land use type also provides jobs (exploitation and transportation) for local farmers who do not have much land or a steady job. A small trader normally purchases product, then transports it to companies to sell.

Rice is the main food crop for the local people. The total area of rice cultivation for each household is small in comparison with other regions and is divided into many different plots. Rice productivity in A Luoi is the lowest within Thua Thien Hue Province because rice production mainly depends on rainfall. It is necessary to maintain and expand the existing rice area to ensure food security.

Rubber is a perennial industrial crop that has grown in Vietnam under natural conditions for a long time. In A Luoi district, however, rubber just started to be planted during the last 15 to 20 years. Initially, rubber was planted in small areas close to residential areas, where there is a convenient transportation system at the Hong Ha and Huong Nguyen communes. Later, along with the expansion of the rubber latex product market, rubber cultivation was expanded to many different areas. Although the labor value of rubber production is not very high, rubber can be harvested for a long time, ensuring a stable income. However, in A Luoi district, the low farming skills and lack of financial resources is a significant difficulty to cultivate rubber.

Cassava is a traditional crop of farmers who live in hilly areas. Initially, they planted cassava to use as food when other resources were not available. Currently, the local people cultivate cassava to sell to food manufacturers. Cassava does not need a high level of farming skills to cultivate, and they are often planted in poor quality soil. Cassava cultivation does not require financial investment and maintain time. Therefore, cassava will continue to be a vital crop of A Luoi district, even though the consumer market is unstable.

The banana is expected to be a crop for agricultural development in the future. Although the number of farmers planting banana is still small, it has increased gradually during the three last years. At present, banana from A Luoi is sold exclusively to supermarkets in Thua Thien Hue Province. Investment in finance and farming skills is needed for banana cultivation, and therefore is difficult to grow in the district.

Table 2.3. Agricultural production information of A Luoi district.

Criteria	Acacia	Rice	Rubber	Cassava	Banana
Number of household	8,500	6,051	1,207	4,015	365
Average of land area (ha)	1.67	0.29	0.61	0.5	0.36
Input Cost (euro/ha)	750	377	11,510	530	1,500
Productivity (ton/ha)	60	4.30	0.46	15.00	16.50
Gross Output (euro/ha)	2,040	778	27,780	830	2,700
Hired labor (day/ha)	30	0	785	0	40
Familied labor (day/ha)	20	272	3,020	70	60
Price of hired labor (euro/day)	8	0	8	0	8
Usage	Sale	Use for family	Sale	Sale (80%) Use (20%)	Sale
Cultivated time	4 years	4 months	25 years	6-8 months	1 year

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Chapter 3. Assessment of soil quality indicators under different agricultural land uses and topographic aspects in Central Vietnam

Abstract: *Soil quality assessment is valuable for agricultural production. In this research, 155 soil samples at two soil depths were collected from four land use types in an agricultural area of the A Luoi district in the Central Vietnam. Differences of soil organic carbon, soil total nitrogen and soil pH under different land use types and topographic aspects were compared. Soil organic carbon contents in arable land and plantation forest are higher than those in natural forest and grassland ($p<0.05$). Conversely, the soil total nitrogen in natural forest was significantly lesser in comparison to other land use types. Meanwhile there were no significant differences of the soil total nitrogen content ($p<0.05$) among arable land, plantation forest, and grassland. The soil of grassland, natural and plantation forests land use types were more significantly acidic than those of the soils of the arable land use type. Soil organic carbon and soil total nitrogen showed a decreasing trend while soil depth increased in all land use types. The soil pH in plantation forest and arable land use types showed no significant change in relation to soil depth. Significant differences were not found in topographic aspects and soil organic carbon content; however, the different changing trends of soil organic carbon content between land use types and aspects were found. The impact of slope, elevation, farming system or soil texture accounted for the differences in these soil indicators under different land use types in the A Luoi district.*

Keywords: *Land use type; Hilly area; Soil quality; Topographic aspects*

Citation:

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3.1. Introduction

According to the first Revised World Soil Charter, endorsed by The Food and Agriculture Organization (FAO) of the United Nations, "soils are a key enabling resource, central to the creation of a host of goods and services integral to ecosystems and human well-being" [1]. In general, soil quality is the ability of soil to provide nutrients to plants, maintain and improve water and air within the soil, and support human needs [2]. Unfortunately, soil quality is rapidly decreasing in many regions around the world [3]. Many reasons leading to soil quality deterioration, including changes in land use types from forest to arable land [4] and the consequences of intensive land use [5]. Improvement of soil quality because of different land use types or crop rotation can be measured by changes in soil indicators and other parameters [6,7].

Various studies have been conducted to evaluate the soil quality indicators under different land use types [8–10]. The most popular indicators used to assess soil quality are soil organic carbon (SOC), soil total nitrogen (STN) and soil acidity (pH). SOC is fundamental to soil fertility and is a reliable indicator of a soil's biological health [11] as well as its chemical, biological, and physical processes. STN is the primary nutrient used for vegetation growth and is also used as a critical soil quality assessment [12]. Soil pH is one of the most essential soil parameters and essential for agricultural production. Most crops develop best in soil with a pH from 5.5 to 6.5 [13]. In the warm and humid environments of Central Vietnam, soil acidification occurs over time as the products of weathering are leached by water moving laterally or downwards through the soil.

Although the effects of different land use types on SOC, STN, and pH have been widely studied, the results remain inconclusive. Abbasi et al. (2007) [8], Dengiz et al. (2015) [14], and Kalu et al. (2015) [10] found that SOC content in forested land is higher compared to other land use types. Conversely, Jonczak (2013) [15] argued that fallow land has the highest SOC content, whereas Shi et al. (2010) [16] stated that paddy rice has the highest SOC content. Similar to SOC, Chen et al. (2016) [17] reported that STN in croplands was significantly lower than in forested land; however, Moges et al. (2013) [18] argued that STN did not show any significant variation across all land use types. Soil pH also is affected by different land use types [19,20].

In general, the total organic carbon (OC) is the amount of carbon in the soil related to living organisms or derived from them. In Vietnamese soils, total OC usually differs remarkably depending on soil type and topography, typically ranging from 1.0-1.5% of total soil weight. Under rainfed farming systems, it is typically 1% [21]. Increasing the quantity of OC stored in soil may be one option for decreasing the atmospheric concentration of carbon dioxide (CO_2), a major greenhouse gas. This function of OC is also considered in the Vietnamese National Adaptation Strategy to Climate Change.

Increasing the amount of OC stored in soil may also improve soil quality as OC contributes to many beneficial physical, chemical, and biological processes in the soil ecosystem (Figure 3.1). When OC in soil is below 1%, soil health is low, and yield potential (based on rainfall) may be constrained [22].

The quantity of OC stored in soil is the difference between all OC inputs and losses from soil. The primary inputs of OC in rainfed farming systems are from crop residues, plant roots, and animal manure. Inputs of plant material are generally higher when plant growth is denser.

Losses of OC from soil occur through decomposition by microorganisms, erosion of the surface soil, and withdrawal in plant and animal production. During decomposition, microorganisms convert about half of the OC to CO_2. This process is continuous; thus without a steady supply of OC, the quantity stored in the soil will decrease over time.

Losses by erosion may profoundly influence the quantity of OC storage due to the heavy concentration of OC as small particles in the surface soil layer that are easily eroded. In Vietnamese agriculture, erosion can cause the annual loss of less than 5t/ha of soil under crop production [23–25] and up to 150-200 t/ha from soil under bare fallow [26]. Withdrawal of OC in plant and animal production is also an important loss of OC from the soil. Harvested materials such as grain, hay, feed, and forage, all represent the loss of OC for plant and animal production.

Soil quality is simply defined as "the capacity of a specific kind of soil to function" [27], i.e., mainly to provide nutrition to plants and absorb and drain water. The different properties of soil are - texture, moisture, fertility (level of nitrogen, phosphorus, and potassium) and pH level, where the pH is the measure of a soil's acidity or alkalinity.

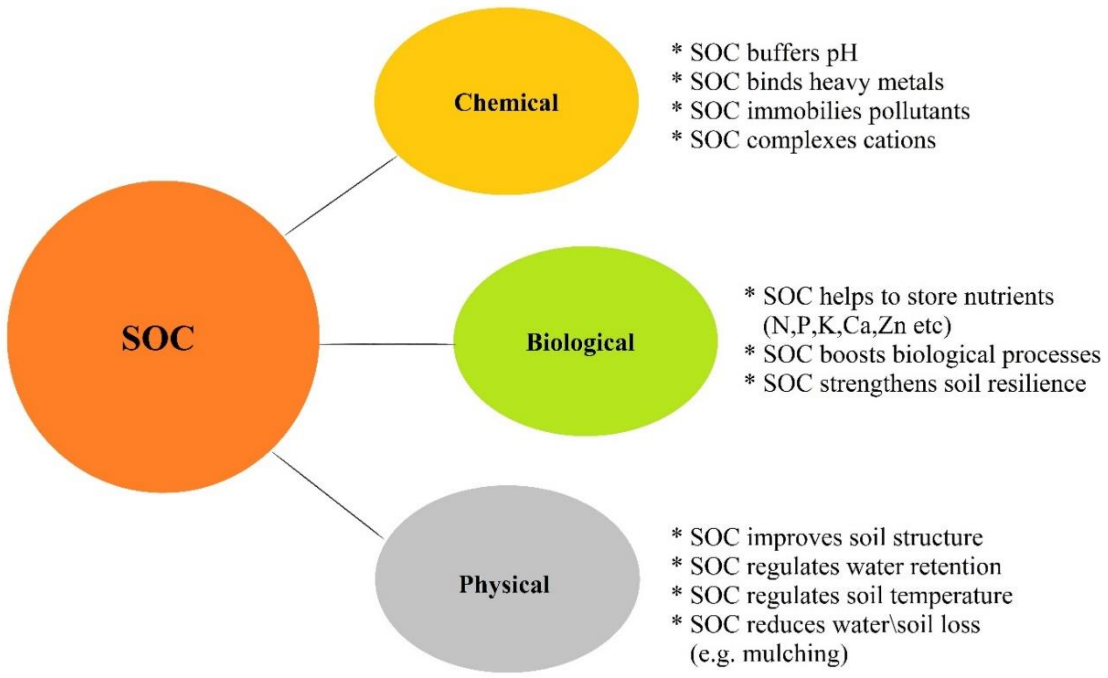

Figure 3.1. Chemical, biological, and physical benefits in soil to which soil organic carbon (SOC) contributes [28].

Hydrology, in terms of surface runoff and soil erosion, has a high impact on current and future OC contents in topsoil in Central Vietnam. The specific hydrological situation of the A Luoi study area has investigated by some authors [29–31].

Soil properties are significantly influenced by spatial factors such as topographic aspect, positions, and climatic conditions. The variations in soil properties and topographic positions are strongly related [32]. According to Pausas et al. (2007) [33], climatic and topographic conditions result in changes of SOC, and changes in OC depend on related topographic position (aspects and slope). In this study, the concept of paired correlation of SOC of land use types and aspects was analyzed.

Among the three macro regions of Vietnam, the Central region is the least developed [34]. The agricultural and forested land areas of the Central region account for 78% total area

[35]. Concerning the impact of different land use types on the ecological systems in Vietnam, the researchers focused on soil erosion, carbon emissions, and climate changes [36–38]. In this area, no soil quality studies have been carried out to date for different types of land use and topographic aspects.

Therefore, the primary objectives of this study, conducted in A Luoi district, are to (i) determine the content of SOC, STN, and pH values for four land use types and (ii) study the differences in SOC, STN, and pH under different land use types, soil depths, and topographic aspects.

3.2. Material and methods

3.2.1. Research area

The study area is located between 107° to 107°30´E and 16° to 16°30´N at around 60km west of Hue city, in Central Vietnam. The area is home to the ethnic majority Kinh and four minority ethnic groups: Ta Oi, Co Tu, Van Kieu, and Pa Ko. By 2015, the population was about 47,115 inhabitants. Agricultural production and collection of forest products are the main livelihoods of most local peoples. The lack of basic resources such as finance and knowledge is one of the main obstacles to sustainable livelihood development, especially in agricultural cultivation [39].

The climate at the research site shows tropical monsoon characteristics with an annual rainy season from September to December. According to statistics from 2005 to 2015, the average yearly precipitation is about 3180 mm. The average temperature reaches the highest in May and the lowest in January at 25°C and 17°C, respectively [40]. The research site has mountainous topography, with a minimum and maximum height from 60 m to 1760 m above sea level, decreasing from West to East. The slope of the terrain is complex and steep with an average of more than 10 degrees. Based on the international classification systems [41], there are four soil types within the research area; including acrisols (ferralic) (75%), acrisols (arenic) (14%), acrisols (humic) (6%), and acrisols (hyperdystric) (5%).

The natural area of A Luoi district is 122,415 hectares (ha) comprising 60,105 ha (49%) of protection forests; 57,492 ha (47%) of agricultural land; 2,318 ha (2%) of water body and 2,500 ha (2%) of residential and infrastructural areas [42].

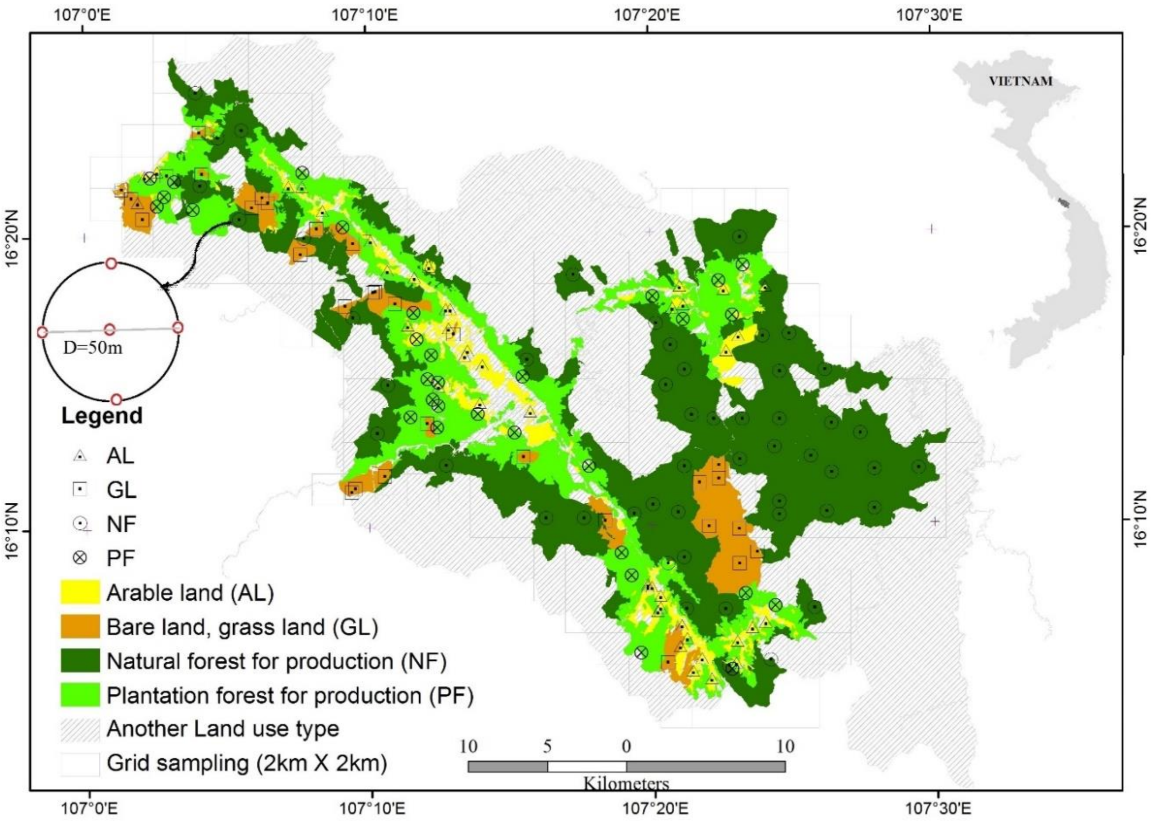

Figure 3.2. Agricultural land use map in 2015 and showing soil sampling position.

Regarding agricultural lands, there are 32,653 ha of natural forests (NF) for production; 15,804 ha of plantation forests (PF) for production; 5,252 ha of grasslands (GL), and 3,783 ha of arable lands (AL) [42].

Table 3.1. Agricultural land use.

Land use type	Symbol	Dominant crops	Area (ha)
Bare land, grass land	GL	Bare land, grass, shrub	5,252
Natural forest for production	NF	Mixed forest, shrub, acacia	32,653
Plantation forest for production	PF	Acacia, rubber	15,804
Arable land	AL	Cassava, rice	3,783

3.2.2. Methods

3.2.2.1. Soil sampling

The soil samples were collected in 2015 and 2016 relying on a soil unit map and a grid sampling method. Soil units in Vietnam result from overlapping a soil type map, land use map, and slope map. In total, there are 78 soil units within the research site. A grid sampling of 2 km x 2 km size for general cases and 4 km x 4 km for large areas and highly homogeneous areas was carried out. The guideline for sampling follows two basic principles: 1) if only one soil unit exists in the grid cell, the sample will be taken at the center of the cell, or 2) if more than one soil unit exists, the sample will be taken at the center for each unit that covers an area larger than 30 hectares in that grid. For each sample, soil material in the layer at 0-30 cm and the layer at 30-60 cm was collected from five points (North, South, East, West, and Center) inside a circle with a radius of 25 m then mixed as a soil sample. In total, 155 samples at these two depths were collected, air-dried, and passed through a 2 mm sieve to remove stones, grass, forest litter, and any material on the soil surface.

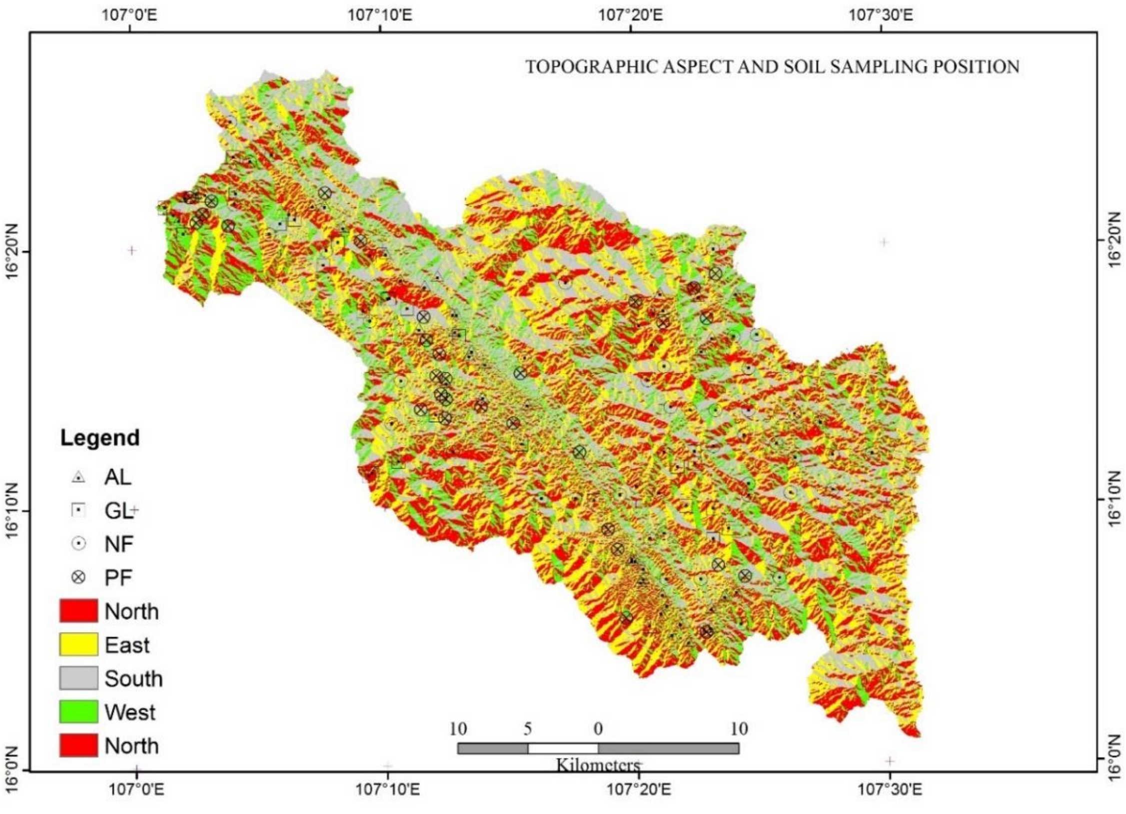

Figure 3.3. Location of sampling sites on a slope aspect map.

3.2.2.2. Laboratory analysis

The soil samples were analyzed to determine SOC, STN, and soil pH. All samples were analyzed at the Laboratory of the Soil Science Department of Hue University of Agriculture and Forestry, Vietnam. SOC was determined by the Walkley-Black method [43], TN was determined by Kjeldahl´s digestion [44], and pH was calculated using a portable pH meter with KCl 1M [45].

3.2.2.3. Statistical analysis

All statistical analyses were carried out in SPSS 16.0. An analysis of the variance test technique (ANOVA) and the post hoc multiple comparisons test were used to evaluate the differences in soil indicators between different land use types, tested with a confidence interval of 95%. A Paired-samples T-test function was used to evaluate the difference of SOC, TN, and pH between the two soil depths layers [46].

We extracted aspects of land use types at the sample points by using the ASTER Global Digital Elevation Model (DEM) with 30 m resolution, and created a matrix between SOC and land use types. The SOC per aspect of land use type was averaged and the paired-correlation between land use types and aspects were analyzed by using the pairs.panels function in the psych package in R studio Version 0.99.903 – © 2009-2016.

3.3. Results

3.3.1. Soil quality characteristics

Table 3.2 shows the location characteristics of the soil samples for the land use types. GL is located in the steepest terrain with an average slope of 20 degrees, followed by NF (17 degrees), PF (12 degrees), and AL (8 degrees). The trend in elevation is the same for the slope. GL has the highest elevation, whereas PF and AL have the lowest, respectively.

The results of the analysis for the 155 soil samples are presented in Table 3.3. The percent of SOC content was greater in the topsoil layer compared to the deeper layer: 1.30% compared to 0.83%, respectively. Our results are similar to previous studies [47] and showed that SOC is low compared to average levels from a SOC classification by Le and Ton, cited in Nguyen & Klinnert (2001) [21].

Table 3.2. Distribution of the soil samples by slope and elevation.

Land use type	N	Slope (Degrees)			Elevation (m)		
		Max	Mean	Min	Max	Mean	Min
GL	31	52	20	0	1184	618	185
NF	50	34	17	1	945	524	137
PF	31	26	12	3	755	496	111
AL	43	21	8	0	780	496	58

N: number of soil samples

The soils for agricultural purposes in A Luoi district shows light acidity with a pH ranging from 3.60 to 4.68 for the topsoil and 3.60 to 4.90 for the deeper layers, which are consistent with values from other researchers [48–50]. The soil total nitrogen amount varies from 0.05-0.21% for topsoil layers and 0.04-0.15 % for deeper layers. The average quality of STN in agricultural land in A Luoi belongs to the medium level group as Do Dinh Sam and Nguyen Ngoc Binh suggestion for Vietnamese soil (less than 0.1% is poor, from 0.1 to 0.2 is medium, and more than 0.2% is rich) [51].

Table 3.3. Soil quality characteristic of soil samples.

Soil properties	Soil Depth (cm)	N	Min	Max	Mean	SD	Skewness
SOC	0 - 30	155	0.42	3.02	1.30	0.44	0.90
	30-60	155	0.05	2.61	0.83	0.39	0.94
STN	0-30	155	0.05	0.21	0.10	0.03	0.87
	30-60	155	0.04	0.15	0.08	0.02	0.47
pH	0-30	155	3.60	4.68	4.11	0.20	0.11
	30-60	155	3.60	4.90	4.11	0.21	0.35

N: number of soil sample, SD: standard deviation

3.3.2. Soil quality indicator under different land use types

3.3.2.1. Soil organic carbon

The SOC content of the soils in the research site varied from 0.42% to 3.02% for the 0-30 cm soil depth layer and 0.05 to 2.61% for 30-60 cm soil depth layer.

There were significant differences ($p<0.05$) between the AL and PF groups and the NF and GL groups in both soil depths levels. The highest SOC content rate is found in AL (1.50 ± 0.44 for 0-30 cm depth and 1.06 ± 0.45 for 30-60 cm depth), which is not significantly higher than the SOC content of PF. The SOC content of the NF and GL groups were not different at the significance level of 95% in both soil depths, even though the average SOC in NF is higher than GL in the topsoil: 1.18 ± 0.36 compared to 1.10 ± 0.40. However, SOC in NF is lower than GL in the deeper slayer: 0.66 ± 0.25 compared to 0.70 ± 0.28. For the soil depths, there were significant differences in all of land use types between the two soil depths. The SOC content of all land use types in the 0-30 cm layer is higher than the SOC content in the 30-60 cm. The SOC content is presented in Table 3.4.

Table 3.4. Mean value of SOC (%) under different land use types at two soil depths.

Land use type	N	0-30 cm	30-60 cm
GL	31	1.10 ± 0.40^{aA}	0.70 ± 0.28^{aB}
NF	50	1.18 ± 0.36^{aA}	0.66 ± 0.25^{aB}
PF	31	1.43 ± 0.44^{bA}	0.93 ± 0.41^{bB}
AL	43	1.50 ± 0.44^{bA}	1.06 ± 0.45^{bB}

N: Number of samples; within columns, values followed by the same lowercase letter (a, b) are not significantly different ($p<0.05$) between land use types; within rows, values followed by the same capital letter (A, B) are not significantly different ($p<0.05$) between soil depths.

3.3.2.2. Soil total nitrogen

Table 3.5 shows the STN content of the land use types. There was a significant difference ($p<0.05$) of STN content between NF and the remaining land use types in both of soil layers. On the contrary, the STN content in GL, PF and AL show no significant differences at the significance level of 0.05, even though the average value of STN in PF (0.115 ± 0.030) appears to be higher than in GL (0.107± 0.030) and AL (0.104 ± 0.025) for the topsoil layer. The STN concentrations in all land use types of the deeper layer show the same trend as the topsoil layer. The STN content of all land use types change significantly by the depth of soil, with the topsoil, STN content greater than the deeper layer.

Table 3.5. Mean value of STN (%) under different land use types at two soil depths.

Land use type	N	0-30 cm	30-60 cm
GL	31	0.107 ± 0.030^{aA}	0.082 ± 0.021^{aB}
NF	50	0.090 ± 0.029^{bA}	0.070 ± 0.022^{bB}
PF	31	0.115 ± 0.030^{aA}	0.084 ± 0.017^{aB}
AL	43	0.104 ± 0.025^{aA}	0.082 ± 0.018^{aB}

N: Number of samples; within columns, values followed by the same lowercase letter (a, b) are not significantly different (p<0.05) between land use types; within rows, values followed by the same capital letter (A, B) are not significantly different (p<0.05) between soil depths.

3.3.2.3. Soil pH

Table 3.6. Mean value of soil pH under different land use types at two soil depths.

Land use type	N	0-30 cm	30-60 cm
GL	31	4.05 ± 0.19^{aA}	4.00 ± 0.18^{aB}
NF	50	4.05 ± 0.16^{aA}	4.07 ± 0.17^{aB}
PF	31	4.05 ± 0.17^{aA}	4.06 ± 0.19^{aA}
AL	43	4.24 ± 0.18^{bA}	4.26 ± 0.23^{bA}

N: Number of samples; within columns, values followed by the same lowercase letter (a,b) are not significantly different (p<0.05) between land use types; within rows, values followed by the same capital letter (A,B) are not significantly different (p<0.05) between soil depths.

Table 3.6 presents the soil pH value of the land use types. The pH for AL was significantly different and higher than the other land use types in both soil depth levels: 4.24 ± 0.18 for topsoil and 4.26 ± 0.23 for deeper soil. There were no significant differences in the pH values between the remaining land use types together in both soil layers, even though the average value of pH for GL in the deeper layer is slightly lower.

Soil pH was not significantly different with soil depth in PF and AL; however, the pH value in GL and NF change significantly by soil depth.

3.3.3. Soil organic carbon under different aspects

For the topographic aspects, the study focuses only on the topsoil layer and the SOC content. There are 154 soil samples in the North (49), East (39), South (33), and West (33), and one sample plot is in a flat position and not representative of any aspect. The SOC content of aspects in the research varies from 0.95% to 1.58%. The data depicts that the mean of SOC values were 1.38%, 1.23%, 1.33%, and 1.26% on the North, East, South, and West aspect, respectively (Table 3.7).

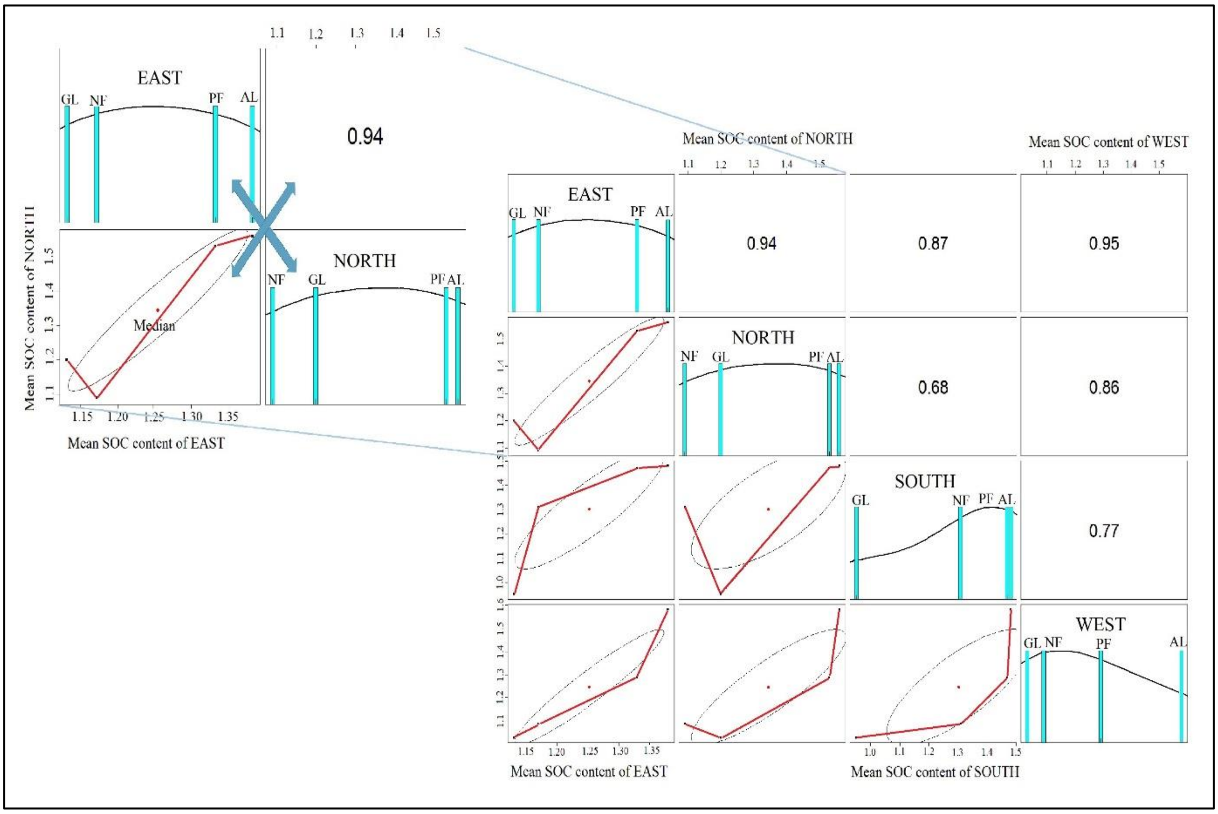

Figure 3.4. Correlation of SOC content changed by land use type between topographic aspects.

The results did not show any significant differences in the mean SOC concentration by topographic aspects using a 95% confidence level. A correlation of SOC content change by land use type between topographic aspects in the topsoil was found (Figure 3.4). The results indicated that the correlation between the East and North aspects is 0.94, the East and South is 0.87, and North and West is 0.86. The highest correlation was found in East and West (0.95), whereas the lowest correlations were found for the South and West (0.77) and North and South (0.68).

Table 3.7. Mean value of SOC content of the topsoil layer under different topographic aspects.

	North (N=49)	**East (N=39)**	**South (N=33)**	**West (N=33)**	**Mean (N=154)**
GL (N=30)	1.20 ± 0.55^{abA}	1.13 ± 0.27^{aA}	0.95 ± 0.52^{aA}	1.03 ± 0.42^{aA}	1.10 ± 0.41^{a}
NF (N=50)	1.09 ± 0.36^{aA}	1.17 ± 0.22^{aA}	1.31 ± 0.48^{aA}	1.09 ± 0.26^{aA}	1.18 ± 0.36^{a}
PF (N=31)	1.53 ± 0.40^{bA}	1.33 ± 0.29^{aA}	1.47 ± 0.53^{aA}	1.29 ± 0.50^{abA}	1.43 ± 0.45^{b}
AL (N=43)	1.56 ± 0.51^{bA}	1.38 ± 0.42^{aA}	1.48 ± 0.33^{aA}	1.58 ± 0.42^{bA}	1.50 ± 0.44^{b}
Mean (N=154)	1.38 ± 0.49^{A}	1.23 ± 0.32^{A}	1.33 ± 0.49^{A}	1.26 ± 0.44^{A}	

N: Number of samples; within columns, values followed by the same lowercase letter (a,b) are not significantly different ($p<0.05$) between land use types; within rows, values followed by the same capital letter (A,B) are not significantly different ($p<0.05$) between topographic aspects.

3.4. Discussions

3.4.1. Soil organic carbon and soil total nitrogen under different land use types

The results differ from other studies on the SOC and STN content in different land use types [52,53], in which the SOC content in forests and grasslands was higher than in cultivated lands in regions of Spain and North China. Conversely, the results from this research indicate that these soil quality indicators are higher in arable land than in forested land with a confidence level of 95% in both soil depths. Therefore, the results of this research further confirmed the findings of Li et al. (2014) [54] and Liu et al. (2011) [55], who found that SOC content in croplands is higher than forested land and grasslands.

The highest STN average occurred for AL and the lowest for NF. These results, therefore, differed somewhat from those in other studies [56,57] in which the forested land had the highest STN storage and croplands had the lowest.

In the A Luoi district, GL and NF reside in of steep terrain, high elevations, whereas AL is located in lower landscape areas (Table 3.2). The study results are consistent with Mu et al. (2015) [58] who determined that the slope factor has a negative effect on the SOC content. A steeper slope might result in more soil erosion, which leads to a decline in SOC. Wei et al. (2010) [59] indicated that for hilly land areas of China, the SOC and STN increased at lower slopes and decreased at the higher slopes. This finding can be used to explain the SOC and STN of AL and PF resulting in higher than NF and GL.

AL is affected by humans via cultivation activities, in which farmers apply fertilizer to provide and improve SOC concentration. On the other hand, management practices that can increase SOC storage due to the increase in carbon inputs, such as fertilizer applications [60–62]. For instance, Aula et al. (2016) [63] stated that nitrogen application significantly increased SOC content when nitrogen rates exceeded 90 kg per hectare. During the cassava cultivation in the hilly areas of the Thua Thien Hue province, farmers often add 1.5 tons of organic fertilizer and 100 kg of nitrogenous per hectare [64]. For rice production in the same areas, farmers applied around 4-6 tons of manure fertilizer and 200 kg of nitrogenous fertilizer per hectare per season (2 seasons per year).

Moreover, after the harvesting season, the belowground residue (e.g., root biomasses) is directly input into the soil system and acting as a major contributor to SOC [65]. Zhang et al. (2016) [66] reported that when the rate of crop residue incorporation was increased from 15%, 50%, and 90%, the average annual SOC increased from 78, 489, and 1005 kg C per ha/year, respectively. In addition, irrigation may increase total crop biomass production and the amount of crop residues returned to the soil which could contribute to the increase of SOC and STN [67].

SOC and STN showed a decreasing trend with increasing soil depth in all land use types which correlates to previous studies [17,68,69]. Plant cycling and carbon inputs from plant roots as well as plant residues could explain the higher levels of SOC and STN in the topsoil [70].

3.4.2. Soil pH under different land use types

In the research site, the average soil pH value was low and belongs to the "Extremely Acid" group as suggested by Smith in Agyare (2004) [71] or "Acid Soil" group as suggestion by local researchers for upland soil in Vietnam [21]. Unlike other studies, Rokunuzzaman et al. (2016) [72] and Moges et al. (2013) [18] reported that soil pH is not significantly different among the land use types, and Chen et al. (2016) [17] claimed that soil pH in croplands is lower than in forested land. Our research found that the highest pH value in both soil depths belongs to the AL group. The results were in agreement with Kiflu & Beyene, (2013) [73] and Liao, et al., (2015) [74], who reported that pH of banana and maize land use areas are higher than grassland, and Abbasi, et al., (2007) [8], who found that the soil pH for forest, grassland, and arable lands was significantly different at 6.95, 7.64 and 7.84 respectively.

The significantly high pH of AL might be attributed to the ameliorating effect of the farming system, namely, lime application. Liming is a regular agronomic practice to improve acidic soils for crop production [75,76]. For cultivated land in Central Vietnam, the farmers usually add 500 kg lime per hectare during tillage [77,78].

3.4.3. Soil organic carbon of different aspects

Even though there are no significant differences at the 95% confidence level, the absolute mean value of SOC concentration for the North and South aspect appears higher than the East and West aspects (Table 3.7). According to the map from World Bank (2017) [79], the North and South of A Luoi district have lower solar radiation in comparison to the East and West part. This may result from cooler temperatures may decreased decomposition rates causing turnover and loss of C to CO_2 is much lower, retaining more C. These results were similar to findings by Lemenih & Itanna, (2004) [80], who reported a negative correlation between SOC content and temperature, and Yimer, et al., (2006) [81], who stated that the SOC content rises up with a decrease in temperature.

Table 3.8. Number of soil samples by topographic aspects and soil texture.

	Silt loam	Loam	Clay loam	Total
North	15	25	9	49
East	11	24	4	39
South	9	23	1	33
West	10	20	3	33

Moreover, we found that there is strong similarity in the change in SOC content in the East and West or East and North aspects in terms of land use types. This may be the consequence of soil texture, the number of samples with clay loam soil texture in the North and East was higher than the other two directions (Table 3.8). Krull et al. (2001) [82] and Plante et al. (2006) [83] have also shown that the soil texture influences SOC content. However, in Central Vietnam, similar studies are needed to confirm the initial observations in this paper.

3.5. Conclusions

The SOC and STN content in all land use types belong to the group "poor" to "medium" in comparison with other regions in Vietnam. The soil is acidic. Most of the soil quality indicators were significantly influenced by different land use systems. The SOC content AL and PF were higher and had significant differences compared to GL and NF at $p<0.05$. STN content in GL, PF, and AL show no significant differences compared together; however, they are significantly higher than NF. Furthermore, all soil indicators decreased by soil depth with significant differences at $p<0.05$, which may result from fertilizer applications and terrain. Meanwhile, pH values in AL are highest and show significant differences with all remaining land use types. The reason for this difference is lime application during cultivation that could improve the soil acidity. The differences in pH values between two soil depths were observed in GL and NF. The significant differences of SOC and topographic aspects did not show at $p<0.05$, however, the correlation in the changing trend of SOC content for land use types between East and West was highest with a value 0.95.

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Chapter 4. Application of ordinary kriging and regression kriging method for soil properties mapping in hilly region of Central Vietnam

Abstract: *Soil property maps are essential resources for agricultural land use. However, soil properties mapping is costly and time-consuming, especially in the regions with complicated topographic conditions. This study was conducted in a hilly region of Central Vietnam with the following objectives: (i) to evaluate the best environmental variables to estimate soil organic carbon (SOC), soil total nitrogen (STN), and soil reaction (pH) with a regression kriging (RK) model, and (ii) to compare the accuracy of the ordinary kriging (OK) and RK methods. SOC, STN, and soil pH data were measured at 155 locations within the research area with a sampling grid of 2 km × 2 km for a soil layer from 0 to 30 cm depth. From these samples, 117 were used for interpolation, and the 38 randomly remaining samples were used for evaluating accuracy. The chosen environmental variables are land use type (LUT), topographic wetness index (TWI), and transformed soil adjusted vegetation index (TSAVI). The results indicate that the LUT variable is more effective than TWI and TSAVI for determining STN and pH when using the RK method, with a variance of 7.00% and 18.40%, respectively. In contrast, a combination of the LUT and TWI variables is the best for SOC mapping with the RK method, with a variance of 14.98%. The OK method seemed more accurate than the RK method for SOC mapping by 3.33% and for STN mapping by 10% but the RK method was found more precise than the OK method for soil pH mapping by 1.81%. Further selection of auxiliary variables and higher sampling density should be considered to improve the accuracy of the RK method.*

Keywords: *land use; ordinary kriging; regression kriging; soil properties*

Citation:

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4.1. Introduction

Soil quality information plays a vital role in land use planning, resource management and site investigation [1]. The most popular indicators to assess soil quality are soil organic carbon (SOC), soil total nitrogen (STN) and soil reaction (pH) [2,3]. The SOC is one of the most important indicators of soil quality for agricultural land use due to its impact on physical, chemical and biological indicators of soil quality, such as soil texture, nutrient availability in soil or electrical conductivity [4]. Moreover, STN and pH have an impact on the growth of plants [5,6]. Reliable information on the spatial distribution of these soil quality indicators is required for sustainable land management and agricultural production [7,8].

There are various methods for interpolation of the spatial distribution of SOC, STN and soil pH, such as inverse distance weighting (IDW) and ordinary kriging (OK) [9–13]. In recent years, researchers have suggested a combination of regression and spatial interpolation, called regression kriging (RK), to determine the spatial distribution of soil characteristics [14–21]. For this method, the selection of auxiliary variables is essential and remotely sensed images are typically the first choice [22]. The OK has been widely used in interpolation techniques due to its simplicity as well as availability in many geographical information systems (GISs) [23,24]. In recent years, RK has become an acceptable method for soil mapping due to its lower cost, and its accuracy often outperforms other methods [25]. However, the accuracy of the RK method is not precise in all of the case studies because it depends on actual soil and environmental variable relationships [26].

For soil characteristic mapping based on environmental variables, researchers [27] often use terrain characteristics as independent variables [27,19,28]. Some researchers use the topographic wetness index (TWI), a local scale index to quantitatively indicate the balance between water accumulation and drainage conditions, as an environmental variable for SOC mapping [29–31] or STN mapping [27,16].

Most researchers [17,18,31–33], however, use normalized difference vegetation index (NDVI) as an auxiliary variable for the regression process. NDVI has been applied to many different aspects of rangeland ecology, but it has limitations. Huete and Jackson [34] found that the soil surface impact on NDVI value was the most significant in areas with a vegetation cover between 45% and 70%. Moreover, NDVI is an estimate of above ground biomass, so if the vegetation is sparse with bare soil present, the soil color may significantly influence the spectral signal. Xue and Su [35] stated that when background brightness is increased, the NDVI also increases. To cope with these inconveniences, Baret et al. [36] suggested an index, the TSAVI, to minimize the soil brightness effect.

LUT is also considered an environmental variable for SOC and STN mapping [37], as well as soil pH mapping [38]. At the current research site, Pham et al. [39] stated that different land use systems significantly influence the SOC, STN, and pH.

Mountains and hills cover eighty percent of Vietnam's territory with complicated terrain. However, eighty-five percent of it are low mountains and hills. The landscape of Central Vietnam is a narrow shape with the hills in the West and small plains along the coast. Among the three macro-regions of Vietnam, the Central region is the least developed [40]. The agricultural and forested land areas of the Central region account for seventy-eight percent of the total area [41], and the agricultural production is the main livelihood of local inhabitants. The lack of soil properties information is one of the main obstacles for agricultural cultivation in Central Vietnam [42]. Therefore, this study conducted in the A Luoi district of Vietnam, aimed (i) to evaluate the best environmental variables to estimate SOC, STN, and soil pH with RK model, and (ii) compare the accuracy of the OK and RK method for soil property mapping.

4.2. Materials and methods

4.2.1. Research area

The study area is located between 107°E to 107°30´E and 16°N to 16°30´N, approximately 60 km west of Hue City, in the low mountainous and hilly region of Central Vietnam. Agricultural production, the collection of forest products, and social subsidies provide the main livelihood for the local people. The lack of primary resources, such as finance and market access, present challenges to these local communities.

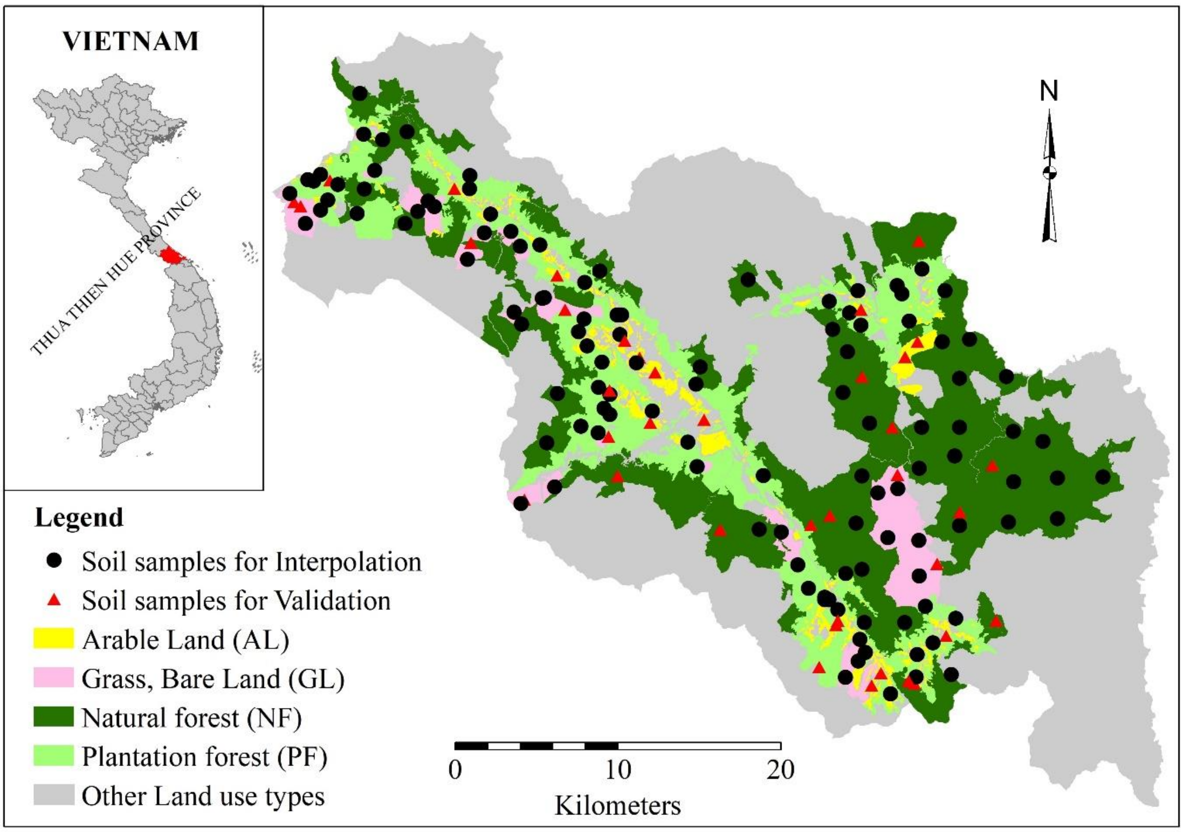

Figure 4.1. Land use map and soil sampling positions.

The climate at the research site exhibits tropical monsoon characteristics with an annual rainy season from September to December. According to statistics from 2005 to 2015, the average yearly precipitation is approximately 3180 mm. The average temperature is the highest in May at 25°C, while the lowest is in January at 17°C [43]. The research site has a mountainous topography, with an elevation between 60 and 1760 m above sea level, which decreases from west to east. The slope of the terrain is complex and steep with an average slope of ten degrees. There are four soil types within the research site: Ferralic Acrisols (75%), Arenic Acrisols (14%), Humic Acrisols (6%), and Hyperdystrict Acrisols (5%). Regarding the soil texture, loam is major (71%), followed by silt loam (24%) and clay loam (5%) [44].

The total area of the A Luoi district is 122,415 hectares (ha), comprising 61,105 ha (49%) of protected forests, 57,492 ha (47%) of agricultural land, 2318 ha (2%) of water bodies and 2500 ha (2%) of residential and commercial area [45].

4.2.2. Remote sensing data

In this research, the near-infrared (NIR) and red bands were extracted from Landsat 8 data, which were downloaded from the United States Geological Survey (USGS) (acquired on 24

January 2015 with cloud cover less than 10%). The data were atmospherically corrected and converted from digital numbers to reflectance values by dark object subtraction (DOS1) algorithm and top of atmosphere reflectance (TOA) tool in QGIS software version 3.2 before calculation of the soil line [46]. The digital elevation model (DEM) was downloaded from USGS and used for calculating the TWI. The data were stored in raster format with a spatial resolution of 30 meters.

4.2.3. Field survey and soil quality analysis

The samples were collected in December 2015 relying on soil unit maps at scale 1:100000 and the grid sampling method. Soil unit maps display the soil type, land use, and slope [44,45]. In total, 78 soil units are present at the research site. A grid sampling of 2 km x 2 km size for general cases and 4 km x 4 km for large areas and highly homogeneous areas was carried out. The guideline for sampling follows two basic principles: 1) if only one soil unit exists in the grid cell, the sample will be taken at the center of the cell, or 2) if more than one soil unit exists, the sample will be taken at the center for each unit that covers an area bigger than 30 ha in that grid. For each sample, soil material in the layer at 0–30 cm was collected from five points (North, South, East, West, and Center) inside a circle with a radius of 25 m then mixed as a soil sample. A total of 155 soil samples were collected, air-dried and passed through a 2 mm sieve to remove stones, grass, forest litter and any other material on the soil surface. Out of these, 117 samples were used for spatial interpolation, and the 38 remaining samples (25% of total number samples) were used for validation of the model [47–49]. Figure 1 shows the locations of the soil samples. SOC was determined with the Walkley–Black method [50], STN was determined via Kjeldahl's digestion [51,52], and pH was measured using a portable pH meter and 1M KCl [53]. The samples were analyzed at the laboratory of the Soil Science Department at the Hue University of Agriculture and Forestry, in Vietnam.

4.2.4. Environmental variables data

4.2.4.1. Transformed soil adjusted vegetation index (TSAVI)

Baret et al. [36] proposed the TSAVI to minimize the effect of the soil background [54]. Baret and Guyot [55] defined TSAVI with the following equation:

$$TSAVI = \frac{\alpha * (NIR - \alpha * R - \beta)}{(R + \alpha * (NIR - \beta) + X * (1 + \alpha^2))} \quad (1)$$

The soil line represents the relationship between the red (R) and near-infrared (NIR) reflectances of bare soil that was proposed by Richardson and Wiegand [56], modeled with the following equation:

$$NIR = \alpha * R + \beta \quad (2)$$

In Equation (1) and (2), α and β are the slope and intercept of the soil line, respectively, NIR is the near-infrared, R is the red reflectance value, and X is soil background adjustment factor (almost in all cases X is 0.08). TSAVI equals zero for bare soil and is close to one for very high leaf area indices.

The soil line extends from an upper value of bright soil with high reflectance in both the R and NIR bands to lower values for darker soils [57]. In this study, the soil line was identified with the quantile regression method. The quantile was set at a number close to zero, for example, 0.00001 [54].

4.2.4.2. Topographic wetness index (TWI)

TWI proposed by Beven and Kirkby [58], also called the compound topographic index, is based on two parameters: upstream contributing area and slope. TWI is represented as:

$$TWI = \ln(\frac{\lambda}{\tan\delta}) \quad (3)$$

where λ is the contributing area and δ is the local slope of the terrain. High values of TWI indicate a high potential for runoff generation. TWI is unitless. In this study, TWI was calculated with the aid of the raster calculator tool in ArcGIS 10.5.

4.2.5. Spatial interpolation

4.2.5.1. Ordinary kriging

OK is one of the most commonly used kriging techniques. The spatial prediction of the unmeasured point x_o is given by predicting the value $Z^*(x_o)$, which equals the line sum of the known measured values (i.e., observed values). Isaaks and Srivastava [59], Cressie [60] and many other researchers provide an elegant and simple description of OK as the following formula:

$$Z^*(x_o) = \sum_{i=1}^{n} \lambda_i Z(x_i) \quad (4)$$

where $Z^*(x_o)$ is the predicted value at the unmeasured position x_o, $Z(x_i)$ is the measured value at position x_i, λ_i is the weighting coefficient from the measured position to x_o and n is the number of positions within the neighborhood searching [61]. A fitted model based on the input data distribution is needed to describe the spatial continuity of the data and show the spatial relationship between the pairs of points. In this study, the OK method was calculated using R software with a framework introduced by Hengl [61] and Omuto and Vargas [62].

4.2.5.2. Regression kriging

RK is a spatial interpolation technique that combines a regression of dependent variables on predictors with kriging of the prediction residuals [63,14]. The following equation calculates the RK interpolation:

$$Z^*(x_o) = \widehat{m}(x_o) + \hat{e}(x_o) = \sum_{k=0}^{p} \hat{\beta}_k * q_k(x_o) + \sum_{i=1}^{n} \lambda_i * e(x_i) \tag{5}$$

where $\widehat{m}(x_o)$ is the fitted deterministic part, $\hat{e}(x_o)$ is the interpolated residual, $\hat{\beta}_k$ are the estimated deterministic model coefficients, λ_i are the kriging weights determined by the spatial dependence structure of the residual and $e(x_i)$ is the residual at position x_i. Thus, the first part of the right-hand side of Equation (5) represents the regression and the second part represents the kriging of the residual. Hengl et al. [14] introduced the process of using the RK method for spatial prediction of soil variables. In this study, RK was conducted using the R software [64–66] with a framework introduced by Hengl [61] and Omuto and Vargas [62].

4.2.6. Validation

Thirty-eight of the 155 soil samples were randomly extracted from the dataset to test the predictive accuracy of the model. This accuracy was evaluated by comparing the observed and predicted SOC, TN, and pH values at validation point locations. In this study, mean error (ME) and root mean square error (RMSE) were selected as validation indices. We used R_I to compare the OK and RK methods and to improve the prediction accuracy index. If R_I is positive, the accurate prediction of RK is higher than that of OK and vice-versa [16].

$$ME = \frac{1}{n} \sum_{j=1}^{n} (Z_{oi} - Z_{pi}) \tag{6}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(Z_{oi} - Z_{pi})^2} \quad (7)$$

$$R_I = \frac{RMSE_{OK} - RMSE_{RK}}{RMSE_{OK}} * 100\% \quad (8)$$

In Equations (6), (7), and (8), ME is mean error, $RMSE$ is root mean square error, n is the number of testing points, Z_{oi} is the observed value at the i^{th} position, and Z_{pi} is the predicted value at the i^{th} position.

4.3. Results

4.3.1. Soil samples data descriptions

The percent SOC of the topsoil layer (0-30 cm depth) varies from 0.42% to 3.02%. Meanwhile, TN ranges from 0.05% to 0.21%, and pH ranges from 3.60 to 4.68 (Table 4.1). High standard deviation values of SOC and STN (compared to the mean of each soil quality indicator value) imply that these values are widely distributed, while low standard deviation values indicate most of the values are close to an average value. The differences in SOC and STN between the samples were substantial, and vice versa for the soil pH. The distributions of all variables were only slightly skewed (with a skewness value less than 1.0), and their median values were very close to the mean values. Therefore, the soil property values of the sampling points follow a normal distribution (Figure 4.2).

Table 4.1. Description of soil samples.

Soil Indicator	Mean	Median	Min	Max	Std. Deviation	Skewness
SOC	1.31	1.29	0.42	3.02	0.48	0.90
STN	0.11	0.10	0.05	0.21	0.03	0.82
pH	4.10	4.11	3.60	4.68	0.19	0.02

The units for SOC and TN are the percentage of soil weight.

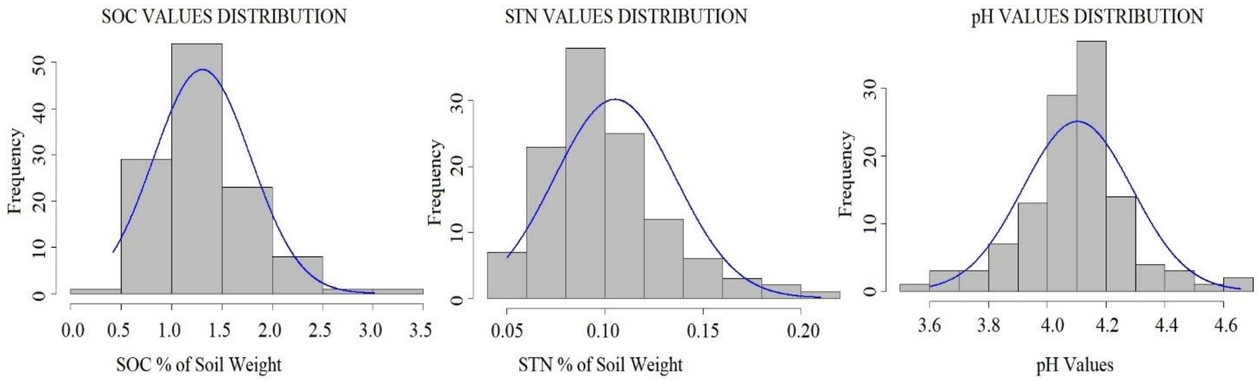

Figure 4.2. Soil quality indicators distribution.

4.3.2. Regression model for soil characteristics mapping

4.3.2.1. Environmental variables calculation

LUT, TSAVI, and TWI are predictor variables (independent variables) in this research. Figure 4.3 shows the spatial distribution of these variables. Based on the 2015 land use map [45], scale 1:50000 and the field survey results, we determined four LUTs belonging to the agricultural land use categories were arable land (AL), grassland (GL), natural forest (NF) and plantation forest (PF). The slope and intercept value of the soil line (α = 1.026, β = 0.00003) was determined for the research site. Using Equation (4), the TSAVI ranges from 0 to 0.57. The TSAVI values of AL are lower than for other land use types. The TWI value of the research site changes from 5.4 to 19.87. Most of the area of GL, PF, and NF have TWI values of approximately 10, while the TWI values of AL are higher than those of other land use types.

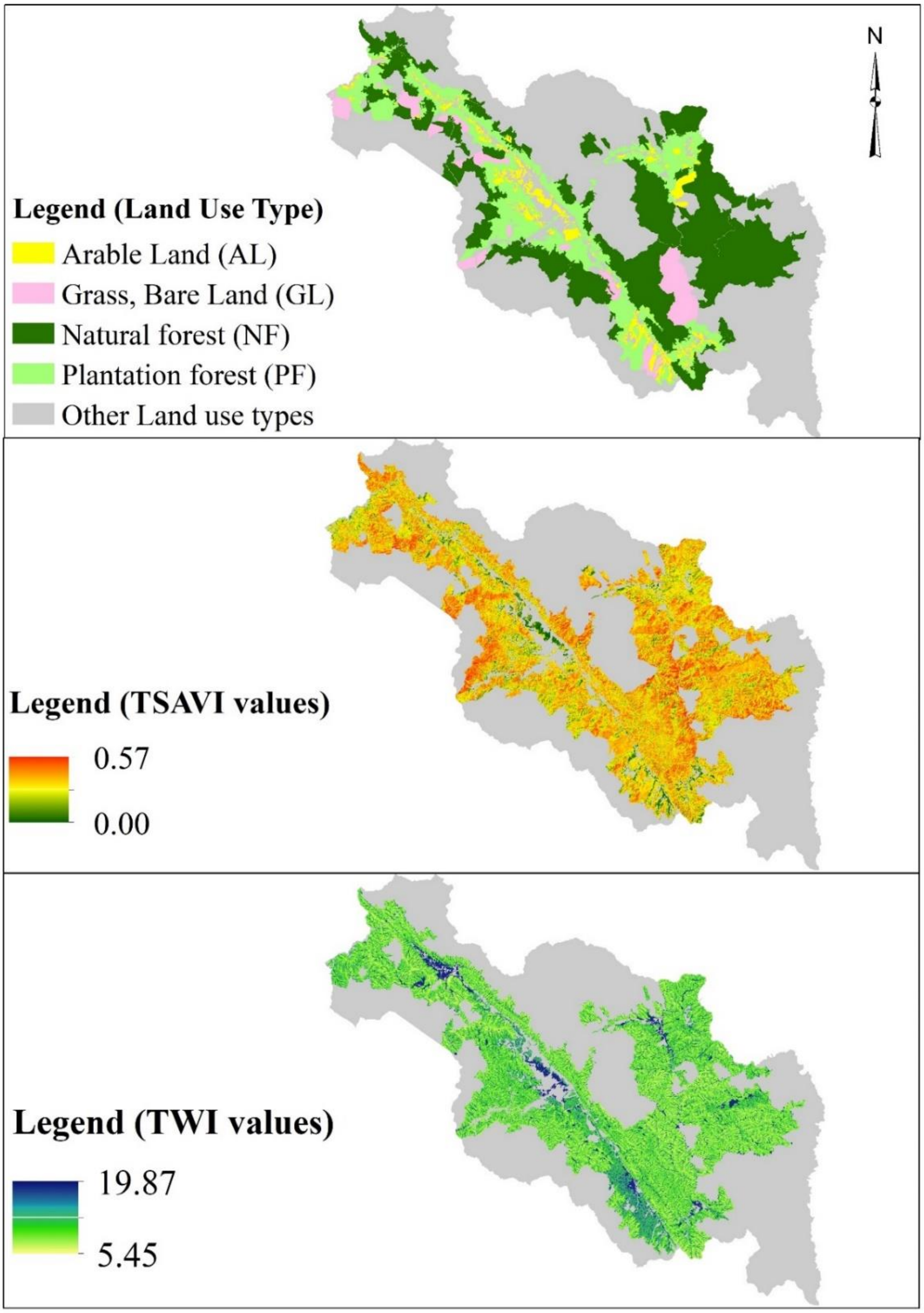

Figure 4.3. Map of environmental variables.

4.3.2.2. Model for regression kriging

Adjusted R squared values are critical to explaining the influence of the independent variables on the dependent variables of the model. The results from Table 4.2 show that the

LUT affects STN and pH (7.00% for STN, 18.40% for pH), whereas a combination of the LUT and the TWI has the most robust impact on the SOC with a variance of 14.98%. Environmental variables affect SOC and soil pH more than they affect STN. Therefore, $y = f(LUT)$ was used for STN and pH mapping with the RK method, while $y = f(TWI, LUT)$ was used for SOC interpolation.

Table 4.2. Variance explanation for models.

Predictive Model	**Variance Explanation (%)**		
	SOC	**STN**	**pH**
$y = f(TSAVI)$	2.08	0.01	4.03
$y = f(TWI)$	7.19	0.01	4.59
$y = f(LUT)$	14.52	7.00	18.40
$y = f(TSAVI, TWI, LUT)$	14.51	5.60	17.15
$y = f(TWI, LUT)$	14.98	6.30	17.77
$y = f(TSAVI, LUT)$	13.91	6.25	17.71
$y = f(TSAVI, TWI)$	7.00	0.01	5.90

The semivariogram depicts the spatial autocorrelation of the measured sample points. Figure 4.4 and Table 4.3 show the semivariogram and residual semivariogram of SOC, STN, and pH data. Both semivariogram models (initial variables and residuals) have approximately the same form, but the residuals semivariogram model has a small difference in the sill, nugget, and range.

The nugget parameter of the SOC semivariogram is very high, meaning that the unexplained variability of this soil indicator is caused by measurement error rather than the short sampling distance. Moreover, the nugget/sill ratio of SOC and pH is 0.56 and 0.86, respectively, indicating that the sampled spatial dependence is weak. This ratio indicates that the SOC value errors are related to sampling distances. The nugget/sill ratio of STN is lower than the ratio of other soil indicators. Since the nugget value is higher than zero, the separated observation by the smallest distances is dissimilar.

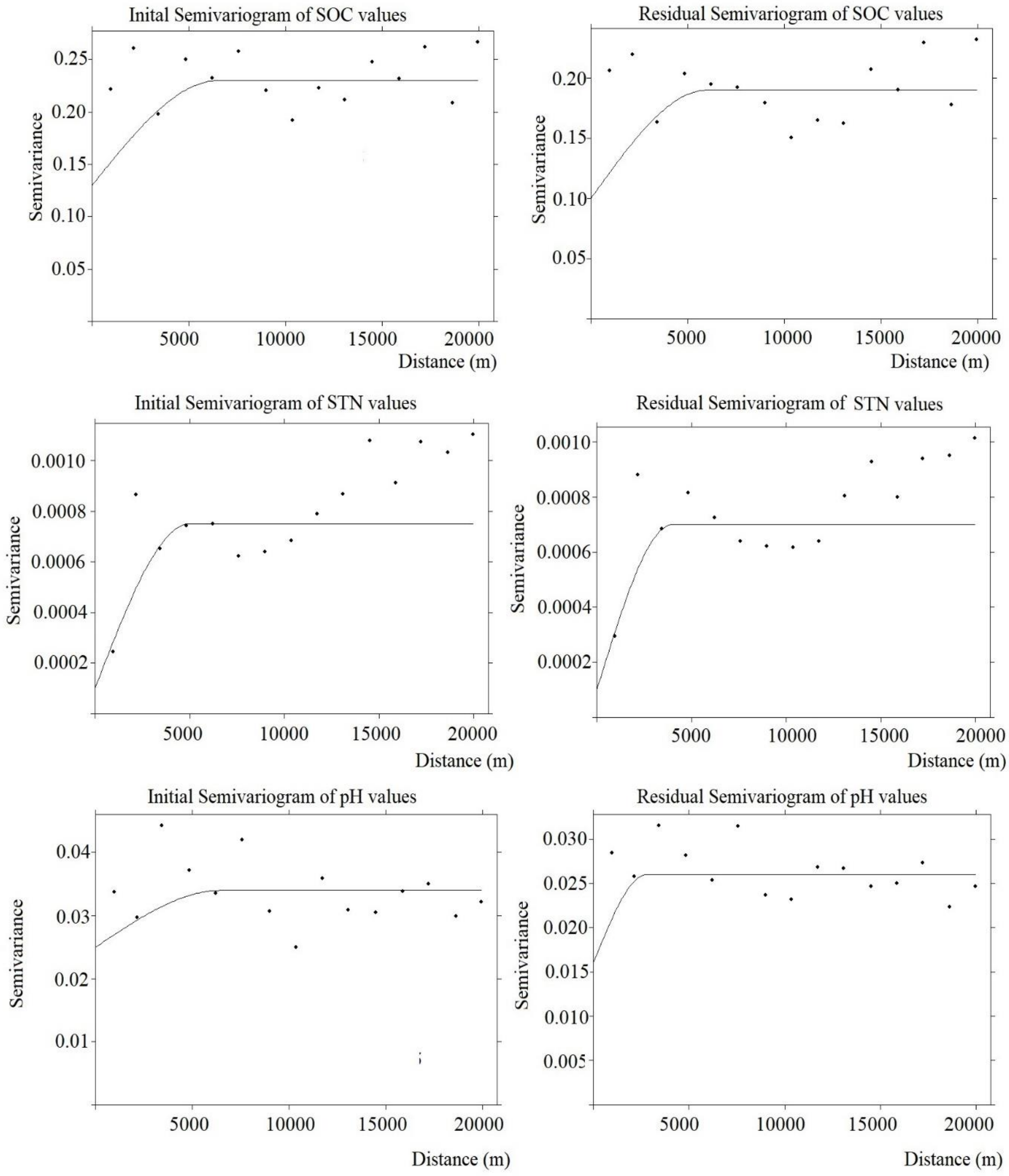

Figure 4.4. Semivariogram of soil organic carbon (SOC), soil total nitrogen (STN), pH (left) and their residuals (right).

Table 4.3. Semivariogram parameters.

Soil Property	Model	Initial Semivariogram			Residual Semivariogram			Nugget/Sill (Initial Data)
		Range (m)	Sill	Nugget	Range (m)	Sill	Nugget	
SOC	Spherical	6500	0.23	0.13	3800	0.19	0.09	0.56
STN	Spherical	5000	7.5×10^{-4}	10^{-4}	4000	7.5×10^{-4}	10^{-4}	0.13
pH	Spherical	6500	0.029	0.025	2800	0.026	0.016	0.86

4.3.3. Spatial interpolation

The spatial prediction maps by OK and RK method are presented in Figure 4.5 for the SOC, STN, and soil pH indicators. The SOC at the research site ranges from 0.89% to 1.78% when interpolated with the OK method. When interpolated with the RK method, the SOC content is somewhat more detailed than the OK method, ranging from 0.62% to 2.10%. The pH varies from 3.94 to 4.25 for the OK method and from 3.86 to 4.40 for the RK method. The STN for both methods does not differ much, 0.051 for the lowest threshold and nearly 0.189 for the highest value. The OK prediction map shows the gradual transition of the detailed level is lower than the transition with the RK method. The influence of auxiliary variables is shown clearly on the maps, which was interpolated with the RK method. For the STN and pH maps, transitions are evident at the boundaries between land use types, however, these changes are recorded at different TWI value locations and boundaries between different land use types on the SOC map as well.

According to SOC classification by Le and Ton, cited in Nguyen and Klinnert [67], SOC in upland soil in Vietnam was divided into three groups (less than 0.58% is low, from 0.58 to 1.16 is medium, and more than 1.74% is high). Regarding the STN, Do and Nguyen [68] suggested three groups for Vietnamese soil (less than 0.1 is low, from 0.1 to 0.2% is medium, and more than 0.2% is high). The results (Figure 4.6) show that there are small differences between the maps obtained by the OK and RK methods. The percentage of area where SOC ranges from 1.16% to 1.74% (medium level) by the OK method is 9% higher than by the RK method, and vice-versa for the remaining SOC contents. Meanwhile, there are more STN values at a low level when interpolated by the RK method compared to the OK method (58% and 53% of the total area, respectively). The difference in the percentage of area for pH values between the RK and the OK method is not significant. In general, the distributions of soil property classes in maps created by both methods are the same.

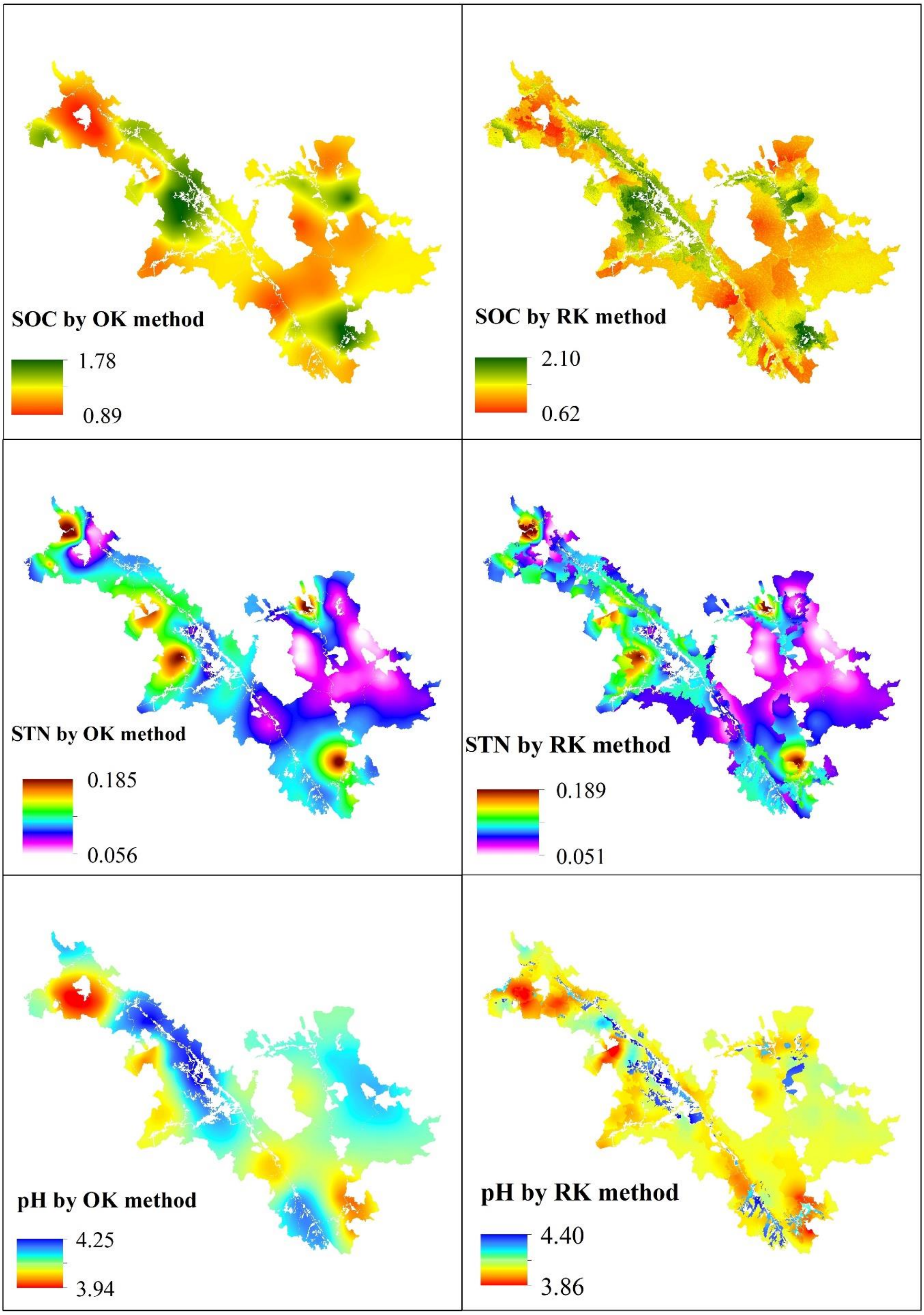

Figure 4.5. Maps of SOC, STN, pH by OK method (left) and by RK method (right).

For an accurate prediction model, the absolute values of RMSE and ME should be as small as possible. Negative ME values indicate that the actual value recorded is higher than the predicted value. For the SOC and STN mapping, the absolute values of both ME and RMSE produced with the OK method are smaller than those generated with the RK method (Table 4.4). This statistical value indicates that the prediction accuracy of OK is higher than RK. The values of R_I show that OK is more accurate than RK (for SOC and STN mapping) by 3.33% and 10.00%, respectively.

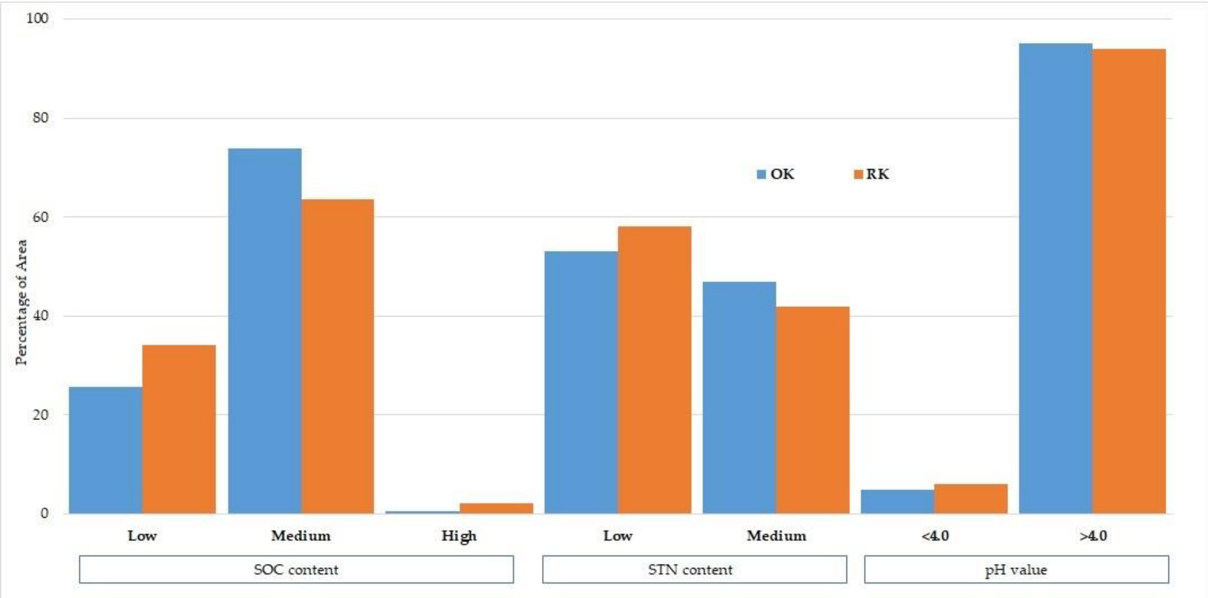

Figure 4.6. Percentage of area for SOC, STN, and soil pH by the OK and the RK method.

Regarding soil pH mapping, the absolute value of ME for the OK method is less than for the RK method, and vice versa for RMSE values. These values show that the sum of the mean errors for the OK method is smaller than for the RK method. However, the mean errors are unevenly distributed, and large errors are more frequent for the OK method. Therefore, the RK method is more accurate than the OK method (by 1.81%) for soil pH mapping.

Table 4.4. Accuracy assessment of ordinary kriging (OK) and regression kriging (RK) method for SOC, STN, and pH mapping.

	SOC		**STN**		**pH**	
	OK	**RK**	**OK**	**RK**	**OK**	**RK**
ME	-0.034	-0.041	-0.008	-0.008	0.001	-0.019
RMSE	0.327	0.337	0.018	0.020	0.202	0.198
R_I	-3.33%		-10.00%		1.81%	

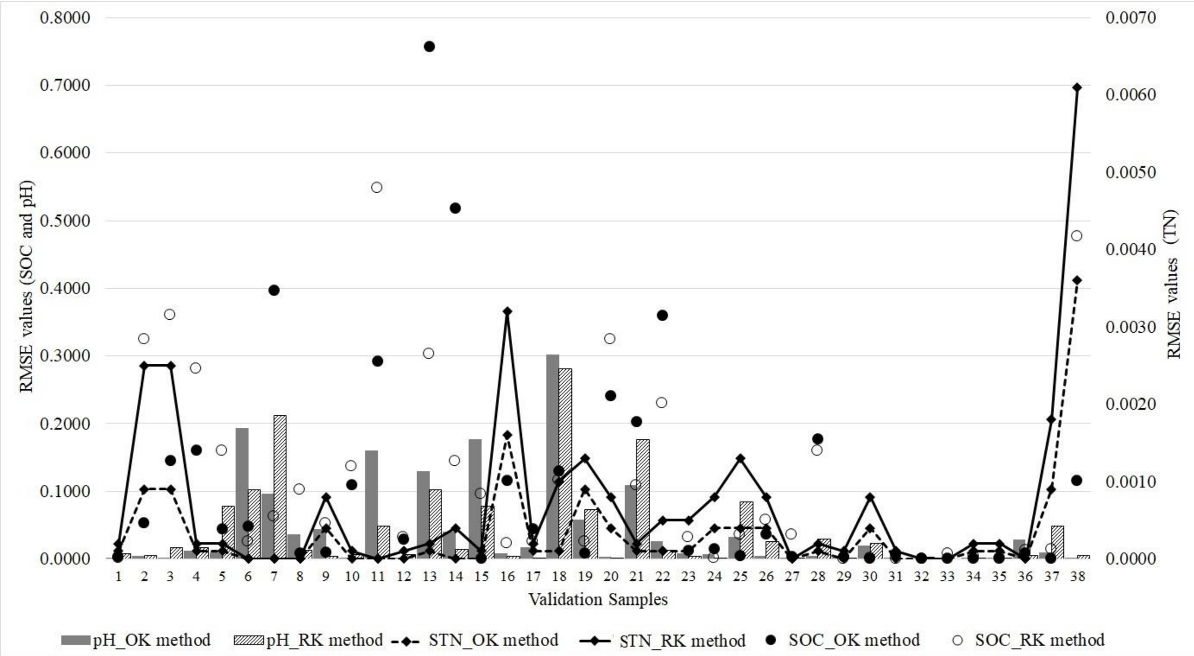

Figure 4.7. Root mean square error (RMSE) values of validation samples.

Figure 4.7 shows the degree of dispersion of RMSE values for observed and predicted values at 38 validation points. These small values indicate that the predicted values are close to the observed values and vice versa. The method with the larger number of smaller RMSE values is more accurate and vice versa. For SOC mapping, the value of RMSE for 25 of the 38 validation samples with the OK method is smaller than with the RK method. Meanwhile, for STN mapping there are ten samples, which have RMSE values that are smaller with the OK method, and only one sample that has a smaller RMSE value with the RK method. There is no difference between the OK and RK of RMSE values for the remaining 27 samples. Again, these data confirmed that for SOC and STN mapping, the OK method is more accurate than the RK method. Regarding soil pH interpolation, the number of validation samples that have small RMSE values is equal between the OK and RK methods. Therefore, although the RK method has higher accuracy, it is not significant for soil pH mapping.

4.4. Discussions

4.4.1. The impact of environmental variables on SOC, STN, and soil pH

Land use has a strong impact on soil properties. Different land use types are managed using different practices, for instance, with the amount and frequency of fertilizer applied [69]. Moreover, our previous research [39] indicated that at the study site, the SOC content of plantation forest and arable land is higher than for other land use types. The highest STN average occurred for arable land and the lowest for natural forest. The pH for arable land was significantly higher than for the other land use types. The impact of land use type on SOC has been analyzed in many studies [70,71,19]. Our results are consistent with the findings of Liu et al. [72], who stated that LUT has the most influence on SOC when compared to other environmental variables. Quantitative studies of the influence of LUT on TN and soil pH spatial interpolation models have not yet been conducted, however, many researchers [16,27,73,74] have indicated that LUT has an effect on STN and soil pH. The influence of the LUT on SOC, STN, and pH is a consequence of farming systems and fertilizer application.

Ließ et al. [75] indicated that TSAVI does not belong to a group of 13 environmental variables that have the most effect on SOC content. Other authors often use NDVI as a predictor for SOC mapping. Ranjan et al. [76], Kumar et al. [17] and Wu et al. [77] found that the correlation of NDVI with SOC is 0.56, 0.66 and 0.67, respectively, for the soil layer between 0 and 15 cm. Our research, however, analyzed SOC in the soil layer between 0 and 30 cm. This depth difference could explain the weak correlation between SOC and TSAVI. With an increase of soil depth, the correlation of SOC and the density of vegetation decreased gradually [77]. This could also explain the correlation between TN and TSAVI, especially at our research site, as the TN content is low. So far, no study has mentioned the relationship between TSAVI and soil pH. West et al. [78] reported that there was no correlation between NDVI calculated from Landsat 8 and soil moisture. Meanwhile, soil moisture has a strong influence on soil pH [79], so the density of vegetation does not show any correlation to soil pH. On the other hand, our research site has a very complex terrain and high annual precipitation. These natural conditions lead to a strong flow rate since the water concentrates in streams instead of dispersing over a wider area. TSAVI has a weak correlation with SOC, STN, and soil pH because of the soil depths and the very steep terrain, as well as the heavy rainfall.

Our results are similar to other authors [30], who also state that there is no significant correlation between TWI and STN content. The spatial STN distribution is more influenced by anthropogenic activity than by topographic features [80]. Regarding the SOC concentration, our results indicate that TWI accounted for only 7.19% of the SOC content. This finding coincided with Pei et al. [29], in the case of using the single flow direction algorithm method to calculate TWI, like in our research. Our results are in agreement with Kumar et al. [81] who reported that the correlation between TWI and SOC in a tropical region (India) was 7%. She et al. [82] also stated that TWI is positively correlated with SOC content. In contrast, Wiesmeier et al. [83] and Yang et al. [84] stated that TWI has a very weak negative correlation with SOC. This difference might be attributed to terrain by slowing down SOC decomposition. Obu et al. [30] found a strong correlation between TWI and SOC at Herschel Island, where the maximum elevation is 180 m above sea level. Gamble et al. [20] found that the spatial distribution of SOC corresponds closely with TWI in a region with an elevation difference of only 6 m. Thus, we assume that there is no correlation between TWI and SOC at 30-m spatial resolution in complex terrain. So far, not much research has studied the influence of the TWI on soil pH, but Seibert et al. [85] found that soil pH increased with TWI. Our results indicate that TWI explained the soil pH variance of 4.59%, which means that this effect is very weak. This finding coincides with Huang et al. [86] who reported that the correlation between TWI and soil pH is not significant, only around 12%. Hjerdt et al. [87] stated that the difference in water flow movement in the area is considered a reason for the inconsistency of TWI. This reason may reduce TWI control on the distribution of soil moisture and soil organic matter [88].

4.4.2. Comparison between ordinary kriging and regression kriging

Zhu and Lin [89] stated that the RK was more accurate for soil property interpolation when a strong relationship existed between predicted soil properties and auxiliary variables, e.g., a coefficient of determination of more than 0.6, indicating that auxiliary variables explain more than 60% of the variance of the predicted variable. In all other cases, the OK was more suitable. Herbst et al. [90] found that the RK was more suitable than the OK for soil mapping when the correlation between soil properties and auxiliary was between 0.2 and 0.55. In our study, the auxiliary variables influenced soil properties by only 14.98% and 7.00% for the SOC and STN, respectively. Therefore, the OK interpolation method is more accurate than the RK method with LUT, TSAVI, and TWI auxiliary variables for SOC and STN mapping. Our results show that with 18.40% variance, the LUT variable improved the soil pH mapping with the RK method. The selection of more auxiliary variables (e.g., elevation, slope, soil moisture) is a possible option to improve the accuracy of the RK method. Wang et al. [91] also stated that RK may be more suitable for spatial predictions in relatively uniform environments, especially those that are suitable for gathering strongly autocorrelated data via regular grid sampling. Table 4.3 shows that the distance between our samples is too large for this criterion. Increasing sampling density is a solution to increase accuracy via the establishment of an appropriate semivariogram. To improve the accuracy of the RK method, Omuto and Vargas [62] suggested mixed-effects modeling, to avoid the failure of the RK model, recognizing that natural soils occur in groups with unique response characteristics depending on soil formation factors.

4.5. Conclusions

In the RK method, LUT is an auxiliary variable that most affects the interpolation model. For soil pH and STN mapping, a single regression of LUT and predicted variables were established for interpolation, whereas multiple regressions of LUT and TWI variables were used for the SOC mapping model.

The interpolated SOC and STN maps show that the OK is more accurate than RK because of the weak correlation between the auxiliary variables and the predicted variables. However, the RK method is better than the OK method for soil pH mapping. The LUT, TSAVI, and TWI at 30-m spatial resolution are not suitable auxiliary variables in the RK method for SOC and STN mapping in this hilly region of Central Vietnam, but the LUT should be considered an auxiliary variable for soil pH mapping with the RK method.

4.6. References

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Chapter 5. Multi-criteria decision analysis for the land evaluation of potential agricultural land use types in a hilly area of Central Vietnam

Abstract: *Land evaluation is a process that is aiming at the sustainable development of agricultural production in rural areas, especially in developing countries. Therefore, land evaluation involves many aspects of natural conditions, economic, and social issues. This research was conducted in a hilly region of Central Vietnam to assess the land suitability of potential agricultural land use types that are based on scientific and local knowledge. In the frame of this research, Participatory Rural Appraisal (PRA); Analytical Hierarchy Analysis (AHP); Geographic Information System (GIS) and scoring based on scientific literature and local knowledge were applied for Multi-Criteria Decision Analysis (MCDA) for land use evaluation. The results of the PRA survey reveal that five plants offer great agricultural potential in the research area, namely rice, cassava, acacia, banana, and rubber. The land suitability of each plant type varies, depending on physical conditions as well as on economic and social aspects. Acacia and cassava represent the most suitable plant types in the research area. Recommendations regarding agricultural land use planning in the A Luoi district are brought forward based on the land evaluation results. The combination of scientific and local knowledge in land assessment based on GIS technology, AHP, and PRA methods is a promising approach for land evaluation.*

Keywords: *Land evaluation; GIS; Analytical Hierarchy Analysis (AHP); Participatory Rural Appraisal (PRA); local knowledge*

Citation:

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5.1. Introduction

Today’s world population of 7.5 billion is projected to rise to 9.7 billion until 2050 [1]. Demographic developments, changing consumption patterns, and climate change are expected to reinforce the pressure on land and to increase the risk of food insecurity, especially in developing countries [2]. While the United Nations, with the second Sustainable Development Goal (SDG), strive to end all forms of hunger and malnutrition until 2030, to date, 793 million people still suffer from undernourishment [3]. The goal of the United Nations can only be achieved if agricultural production growth exceeds population growth through a sustainable intensification of existing, but limited, agricultural land [2]. Meanwhile, land resources are central to agricultural production and inseparably connected with food security [2]. Therefore, research regarding land resources should be carried out in a comprehensive way when considering the physical as well as socio-economic factors [4]. On the regional scale, the active participation of stakeholders can lead to a better and informed decision making process [5].

Vietnam is an agricultural country in Southeast Asia that is characterized by population pressure and land scarcity [6]. In 2016, 64% of the Vietnamese population resided in rural regions and 42% of the total labor force worked in the agricultural sector [7]. Therefore, the effective management of land resources for agricultural production in Vietnam is an essential requirement for food security and sustainable rural development. Despite the area of agricultural land expanding from 22% in 2005 to 39% in 2016, the productivity and the value of agricultural production in Vietnam still remains lower in comparison to other countries of the region, such as Thailand and China [7]. The inappropriate use of agricultural land is a major constraint to agricultural production in Vietnam [8].

Land evaluation is a process for predicting the land’s suitability for a specific land use type (LUT) in a given area. Land evaluation provides a rational basis for land use planning [9], especially in developing countries, where an increase of arable land, often results in negative effects of land degradation and environmental issues [10]. Distinct methods and models have been applied for land evaluation, such as Linear Combination, Simple limitation, fuzzy-logic modelling, the use of Artificial Neural Networks, and the Analytical Hierarchy Process (AHP)

[11–16]. Despite some limitations, the AHP is still the most commonly applied method for land evaluation, especially on a small scale [17–19].

Determining the requirements for a LUT and scoring the suitability level has a significant impact on land evaluation results [20]. The Food and Agriculture Organization of the United Nations (FAO) (1996) [21] suggested that climate, soil, and landform are the necessary requirements for land evaluation from an ecological perspective. Sys et al. (1993) [22] provided the reference values for physical crop requirements for fifty crop types that are commonly cultivated in tropical and sub-tropical regions. These values have been applied by many researchers for land suitability evaluation [23–27]. However, the crop requirements that were provided by Sys et al. (1993) [22] are not detailed enough for smaller areas with specific characteristics.. Therefore, most of the researchers modified the original crop requirements document to adapt to local conditions, experiences, and data availability [28,29]. Local knowledge in land evaluation plays a significant role in land use decision-making and land management in rural areas [30]. The integrated method of scientific and local knowledge involvement in land evaluation can lead to improved sustainable agricultural production [31]. A combination of biophysical surveying, spatial modeling, and participatory methods are needed for effective land evaluation, according to the FAO (2007) [20].

Research on land evaluation requires a large amount of spatial data, which Geographical Information Systems (GIS) are capable of easily and efficiently handling. Therefore, many researchers have used GIS for land evaluation [32–34], a process, which enables the integration of multiple attributes and different criteria that are involved in decision-making. Land evaluation can be seen as a multi-criteria decision analysis (MCDA) process [35], which, when combined with GIS, can become a powerful approach for land evaluation [34,36]. GIS techniques play an indispensable role in spatial analysis, whereas MCDA provides a rich collection of tools for structuring decision problems, as well as evaluating and prioritizing alternative decisions [34].

This paper describes the integration of GIS and AHP methods that are based on scientific and local knowledge to determine the land suitability for some potential agricultural LUTs in a hilly district of Central Vietnam.

5.2. Material and methods

5.2.1. Research area

The study area “A Luoi district” is located between 107°E to 107°30'E and 16°N to 16°30'N and it is situated around 60 km west of Hue city, in Central Vietnam (Figure 5.1). The climate at the research site shows tropical monsoon characteristics with an annual rainy season from September to December. The average yearly precipitation amounts to 3180 mm, according to statistics from 2005 to 2015. The average temperature reaches its maximum in May and its minimum in January at 25°C and 17°C, respectively [37]. The research site exhibits a low mountainous topography, with elevations ranging from 60 m to 1760 m above sea level, and decreasing from west to east. The slope in the area is complex and steep, with an average of more than 20 degrees. According to the international soil classification system [38], there are four soil types within the research area, including acrisols (ferralic) (75%), acrisols (arenic) (14%), acrisols (humic) (6%), and acrisols (hyperdystric) (5%) [39].

A Luoi district has an area of 122,415 hectares (ha), of which 60,105 ha (49%) are covered by protected forests, 57,492 ha (47%) are agricultural land (including production forests), 2,318 ha (2%) represent water bodies, and 2,500 ha (2%) are residential and infrastructural areas [40].

Four ethnic minority groups are living in the research area, namely the Ta Oi, Co Tu, Van Kieu, and Pa Ko, accounting for 75% of the total population. The majority Kinh people occupy 25%. In 2015, the total population was 47,115 inhabitants with 12,405 households. The households living below the poverty line occupied 37% of the total households. The poverty line was defined as a monthly income per person less than 26 Euro [37].

Agricultural production and collection of forest products are the main livelihoods of the majority of local people. Agricultural labor accounts for 75% of the entire labor force [37].

Acacia, rice, rubber, cassava, and banana are the five main agricultural crops. In addition, there are a number of minor crops, such as corn, peanuts, and vegetables, which occupy a rather small area and do not have a significant impact on local people’s livelihoods [37]. The lack of basic resources, such as financing options and modern agricultural knowledge, is one of the main obstacles to sustainable livelihood development, especially in agricultural cultivation [14].

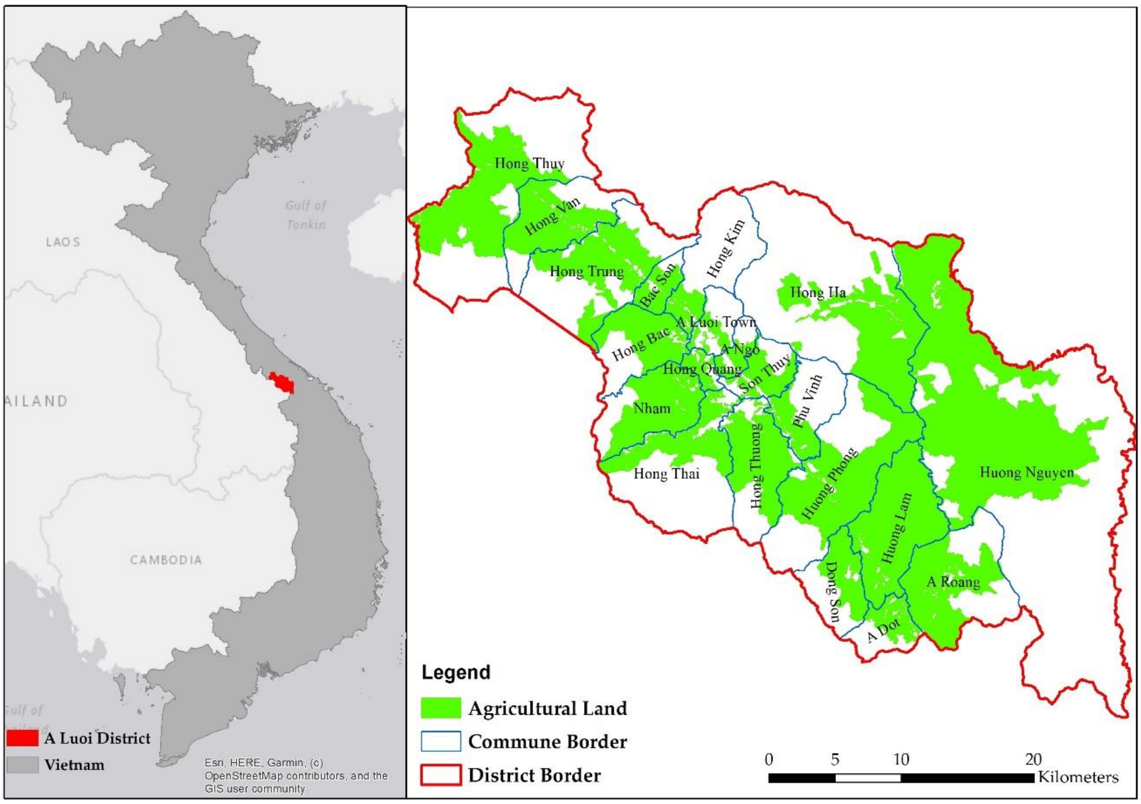

Figure 5.1. Research site and agricultural land use area.

5.2.2. Material

Input information plays an essential role for land evaluation. For each LUT, different values and ranges of criteria exist, defining the different suitability levels. For the selection of criteria, the available data, the cultivation history, and both local and worldwide knowledge need to be considered [41]. The available datasets for land evaluation included geospatial as well as descriptive information. In total, six teen land characteristics were chosen as the input layers for the land evaluation process listed in Table 5.1.

Table 5.1. List of data sets used in this study.

Criteria	Data Source	Map Method
Physical Criteria		
Soil type Soil depth Soil texture	Soil map of Thua Thien Hue province (1:100,000) issued by NIAPP in 2005 [39].	Convert from Mapinfo format (Tab) to ESRI format (Shp)
Soil organic carbon Soil total nitrogen Soil pH	Soil survey data of 155 soil sampling [42].	Ordinary kriging (resolution at 30 meters)
Elevation Slope	Digital Elevation Model (DEM), resolution at 30 meters [43].	Original data
Precipitation	Average annual precipitation from 2005 to 2017 based on three meteorological station in Thua Thua Hue province [44].	Inverse Distance Weighting (resolution at 30 meters)
Economic Criteria		
Financial ability of family Accessibility of farming equipment Labor income per day Ability to sell product	Group discussion/Participatory GIS and Statistical data [37]	Community-wise
Social Criteria		
Poverty rate Labor force availability Access to information Farming skills	Individual discussion/ Participatory GIS Statistical data [37]	Community-wise

5.2.3. Methods

5.2.3.1. Participatory rural appraisal (PRA)

The PRA method enables the capturing of opinions on farmers and other key actors in agricultural and rural research [45]. In our study, the PRA method was used to select the potential crops as well as the assessment of physical and socio-economic aspects with respect to land suitability evaluation. The group discussion was implemented in eleven focus groups, with three to five people per group. The groups consisted of members of the Agricultural Department of the commune or district, the Natural Resources and Environment Department, the Labor and Social Affairs Department, and the Industry and Commerce Department of A Luoi district. Additionally, members of the district or commune committees, academics from Hue University, and farmers of the region participated in the discussions. Moreover, individual interviews were conducted with soil scientists and agronomy experts for the land evaluation regarding physical criteria (Table 5.2).

Table 5.2. Participants in PRA method.

Participants	**Number of participants**												
	Group Discussion for Crops Selection					Online and Individual Discussion for Physical requirements	Group Discussion for Economic requirements						Individual Discussion for Social requirement
Outside Experts						9							
Local Experts						21							
District's Agriculture and Rural Development Dept.	1						1						
Hue University of Agriculture and Forestry	1										2		1
District's People Committee	1						1						
Hue University of Economy											2		
Natural Resources and Environment Dept.		1					1						
District's Labor and Social Dept.		1											1
District's Commerce Dept.		1					1						
Commune's People Committee			1	1	1		1	1	1	1			
Commune's Agricultural Dept.			1	1	1			1	1	1			
Farmers			3	3	3			3	3	3			
Agricultural Companies												1	
Small Traders												2	

Center Rural Development in Central Vietnam																	1
Farmer’s Union																	1
Total	21	3	3	5	5	5	30	30	27	5	5	5	5	4	3	4	4

(Sources: Survey in year of 2017 & 2018)

5.2.3.2. Criteria weighting according to analytical hierarchy process (AHP)

The AHP theory that was developed by Thomas L. Saaty (1987) [46] is an MCDA approach. In scientific research on GIS-based land suitability evaluation, the approach is frequently applied for criteria weighting [15,47–50]. The AHP is a method for deriving a priority scale through pairwise comparison of attributes based on participant judgments [51]. The weighting of criteria through the AHP method was implemented, as follows:

(1) Selection of criteria and setting-up a hierarchy structure.

The hierarchical structure is composed of three levels with the overarching goal of determining the land suitability index for each LUT (Figure 5.2). The second and third levels show the criteria and sub-criteria influencing the decision. Each sub-criterion has different attributes describing specific characteristics, which have influence on the scoring algorithm for various LUTs. These characteristics need to have substantial influence on the productivity, feasibility, or sustainability of the agricultural land use [52]. In addition, critical values and a notable variation of the criterion must be prevalent within the study area [53]. The final set of sub-criteria were selected and categorized with reference to the relevant literature [48,54–57], local expert knowledge, as well as local cropping guidelines that were provided by Nguyen et al. (2015) [52].

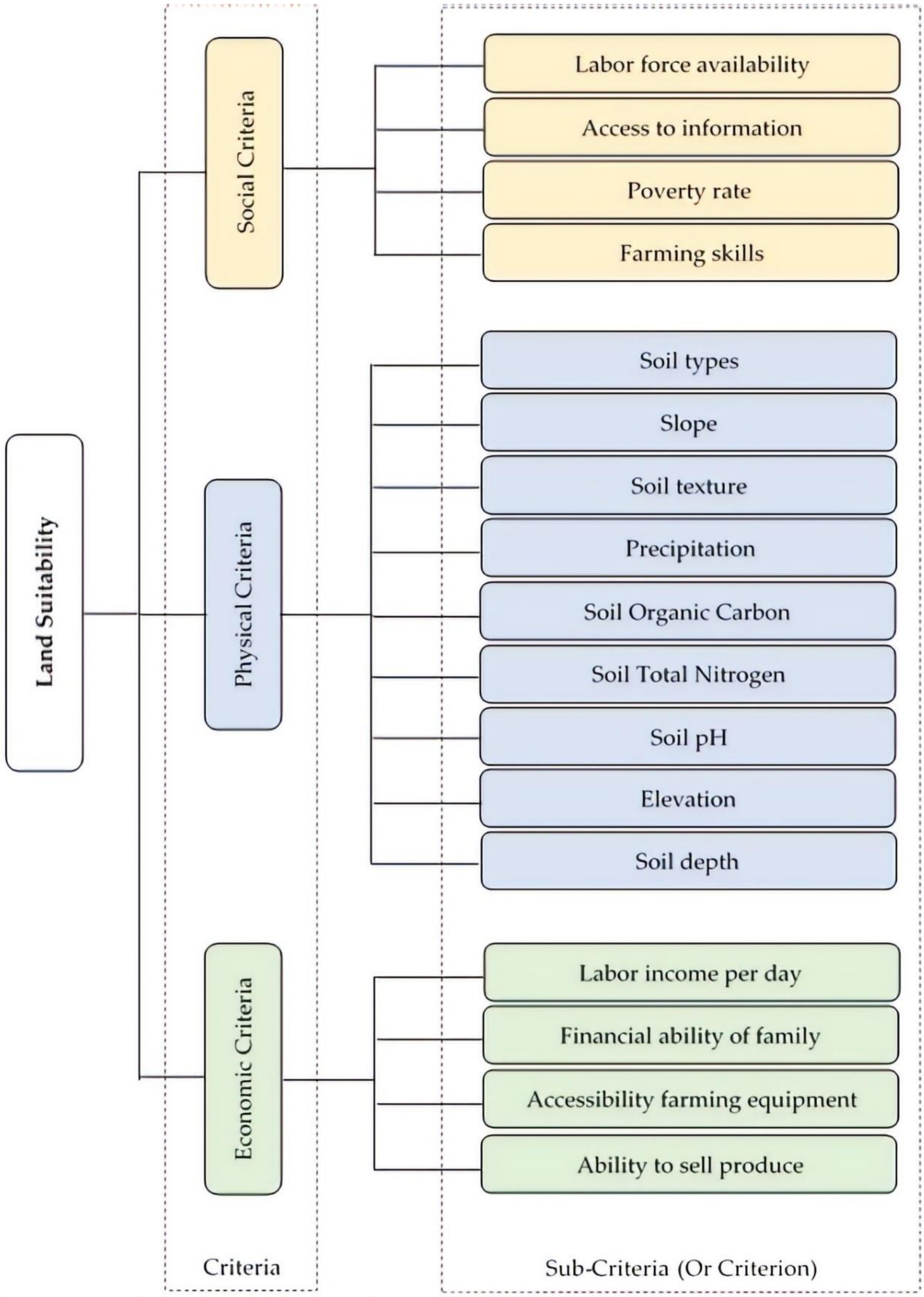

Figure 5.2. Hierarchical structure of the land suitability evaluation.

(2) Construction of pairwise comparison matrices according to the relative importance of each criterion (or sub-criterion).

The comparison matrices were derived from the experts' judgments and constructed, as described by Mu and Perevra-Rojas (2017) [58]. A numerical scale that was developed by Saaty (2008) [51] was used to compare these criteria (or sub-criteria), as shown in Table 5.3.

Table 5.3. Verbal and numeric scale for the pairwise comparison of criterion according to the analytical hierarchy process

Numeric scale	Response alternatives of experts
9	Criterion i is extremely more important than criterion j
7	Criterion i is strongly more important than criterion j
5	Criterion i is more important than criterion j
3	Criterion i is slightly more important than criterion j
1	Criteria i is equally important as criterion j
1/3	Criterion i is slightly less important than criterion j
1/5	Criterion i is less important than criterion j
1/7	Criterion i is strongly less important than criterion j
1/9	Criterion i is extremely less important than criterion j

The geometric mean was applied to synthesize group judgments, as it represents the only mathematically correct way to aggregate reciprocal judgments [59,60]. The Original Matrix (A), which compares the priorities of all criteria against each other, was constructed.

$$A = \begin{pmatrix} 1 & C_{12} & C_{1i} & C_{1j} & C_{1n} \\ C_{21} & 1 & C_{2i} & C_{2j} & C_{2n} \\ C_{i1} & C_{i2} & 1 & C_{ij} & C_{in} \\ C_{j1} & C_{j2} & C_{ji} & 1 & C_{jn} \\ C_{n1} & C_{n2} & C_{ni} & C_{nj} & 1 \end{pmatrix} \quad (1) \qquad C_{ij} = \left(\prod_{k=1}^{m} a_{ijk}\right)^{\frac{1}{m}} \quad (2)$$

where:

C_{ij} is level of importance of criterion i as compared to criterion j

a_{ijk} is level of importance of criterion i as compared to criterion j according to expert k^{th}

m is the number of experts involved in the discussion

Subsequently, the Normalized Matrix (B) is calculated from *A* as Lee et al. (2012) [61].

$$B = \begin{pmatrix} \bar{C}_{11} & \bar{C}_{12} & \bar{C}_{1i} & \bar{C}_{1j} & \bar{C}_{1n} \\ \bar{C}_{21} & \bar{C}_{22} & \bar{C}_{2i} & \bar{C}_{2j} & \bar{C}_{2n} \\ \bar{C}_{i1} & \bar{C}_{i2} & \bar{C}_{ii} & \bar{C}_{ij} & \bar{C}_{in} \\ \bar{C}_{j1} & \bar{C}_{j2} & \bar{C}_{ji} & \bar{C}_{jj} & \bar{C}_{jn} \\ \bar{C}_{n1} & \bar{C}_{n2} & \bar{C}_{ni} & \bar{C}_{nj} & \bar{C}_{nn} \end{pmatrix} \qquad (3) \qquad \bar{C}_{ij} = \frac{C_{ij}}{\sum_{i=1}^{n} C_{ij}} \qquad (4)$$

where:

$\bar{C}_{ij}$ is normalized value of C_{ij}

$\sum_{i=1}^{n} C_{ij}$ is sum of C_{ij} by column j from matrix A

n is number of compared criteria

From the matrix B, the criteria weights can be derived, as follows:

$$w_i = \frac{\sum_{j=1}^{n} \bar{C}_{ij}}{n} \qquad (5) \qquad W = \begin{pmatrix} w_1 \\ w_2 \\ w_i \\ w_j \\ w_n \end{pmatrix} \qquad (6)$$

where:

w_i is the weight of criterion i

$\sum_{j=1}^{n} \bar{C}_{ij}$ is sum of C_{ij} by row j from matrix B

(3) Validating the consistency of the final matrix of judgments.

A certain degree of inconsistency can be expected for criteria weightings based on group judgments. The consistency ratio enables the validation of the participant's answers by giving some indication on the compatibility and rationality between compared criteria. The consistency ratio was calculated, as suggested by Mu and Perevra-Rojas (2017) [58] and Saaty (1987) [46].

$$CR = \frac{CI}{RI} \qquad (7)$$

where:

CR is Consistency Ratio

RI is Random Index has already been provides by Saaty (1987) as Table 5.4.

Table 5.4. Random index based on number of criteria.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

CI is Consistency Index (CI) is then obtained by calculating:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (8) \qquad \lambda_{max} = \frac{\sum \frac{\sum_{j=1}^{n} w_i * C_{ij}}{w_i}}{n} \qquad (9)$$

According to Saaty (1987) [46], an inconsistency of 10% is acceptable. Hence, the weights of a judgment matrix characterized by a CR ≤ 0.1 can be used for further analysis.

5.2.3.3. Deriving scores for criteria levels

The level of each criterion ranges between the minimum and maximum values in the region, which results in a distinct LUT performance, depending on the respective LUT. Therefore, the scores need to be assigned indicating the suitability level of each attribute of each criterion for a given land use type [9].

Many authors [55] refer to the land evaluation guidebook by Sys et al. (1993) [22], which summarizes crop requirements for the tropics and sub-tropics. However, this guideline shows significant shortcomings, as it does not provide information regarding some essential criteria (soil total nitrogen, elevation, soil type), and additionally does not contain reference values for acacia requirements. Moreover, no information on economic or social criteria are given by Sys et al. (1993) [22], which are, for the growth of some crops, equally important as the physical characteristics of an area. Due to these reasons, we introduced an attribute scoring based on the opinions of local stakeholders that were gathered from the PRA survey, in addition to the common scoring approach that was derived from Sys et al. (1993) [22]. We combined the scores according to Sys et al. (1993) [22], where possible, with scores that were derived from the PRA survey and assigned a weight of 50% to each scoring approach in the final suitability map. In those cases, in which the literature does not provide any information, the

PRA scores were fully applied for further analysis. A scale from three to nine was used to reflect the increment from a very unsuitable condition to very suitability conditions for a particular LUT (Table 5.5).

Table 5.5. Scale for scoring according to PRA method.

Score (X_i)	**Definition**
9	Criterion is suitable for evaluated LUT without any concerns.
7	Criterion is suitable for evaluated LUT with few concerns.
5	Criterion may be suitable for evaluated LUT with many concerns.
3	Criterion is unsuitable for evaluated LUT.

As result of PRA method with many participants in local region, a threshold of 5.0, which is equivalent to the level N in FAO-terms, is used as a threshold underneath which the area is unsuitable for the evaluated LUTs and will be excluded from further analysis in our research.

5.2.3.4. Suitability classification

The suitability can be measured with the suitability index (S_i) (Table 5.6), which represents a function of the weight and the score of each level of criterion regarding certain LUT. According to Huynh (2008) [14], the suitability index for one land mapping unit (LMU) and one LUT is described, as follows:

$$S_i = \sum_{i=1}^{n} \bar{X}_i * w_i \quad (10) \qquad \bar{X}_i = \frac{\prod_{v=1}^{u} X_{iv}}{u} \quad (11)$$

where:

S_i = suitability index for a particular LMU and LUT

$\bar{X}_i$ = Score of i^{th} criterion

Table 5.6. Scale for Suitability Index (S_i) for Land Evaluation.

PRA	Literature	Definition
8-9	S1(0)	Suitability of LMU is high and satisfies all considered criteria.

7-8	S1(1)	Suitability of LMU is high and satisfies most important considered criteria.
6-7	S2	Suitability of LMU is medium and satisfies most considered criteria, but some criteria are not satisfied.
5-6	S3	Suitability of LMU is low and satisfies some considered criteria, but most considered criteria are not satisfied.
Less than 5	N	Not Suitable

As a result of the PRA survey, a threshold of 5.0, which is equivalent to the level N according to Sys et al. (1993) [22], is used as a threshold for the areas that are unsuitable for the evaluated LUTs, which will be excluded from further analysis in our research.

5.2.3.5. GIS based land suitability evaluation

Seventeen thematic layers were created corresponding to the seventeen selected criteria for the land evaluation process. These maps were classified based on the PRA survey and literature. Afterwards, an intersection of all the layers was carried out to receive the land mapping units. The maps of land mapping units form the basis for analyzing the physical, economic, and social suitability of each land unit with respect to certain crop types. The calculation of suitability indices was performed using the attribute table of the vector layers, as suggested by Huynh (2008) [14]. The output of the suitability mapping will contain fifteen maps for all five crops showing their suitability with respect to the physical, economic, or social criteria. To receive the overall suitability, the three criteria-maps need to be overlaid for each crop. The weighted sum is used to create overall suitability maps for each crop. From the suitability maps of each kind of crop, the highest position tool was applied to analyze the most suitable land use for a particular land unit (Figure 5.3).

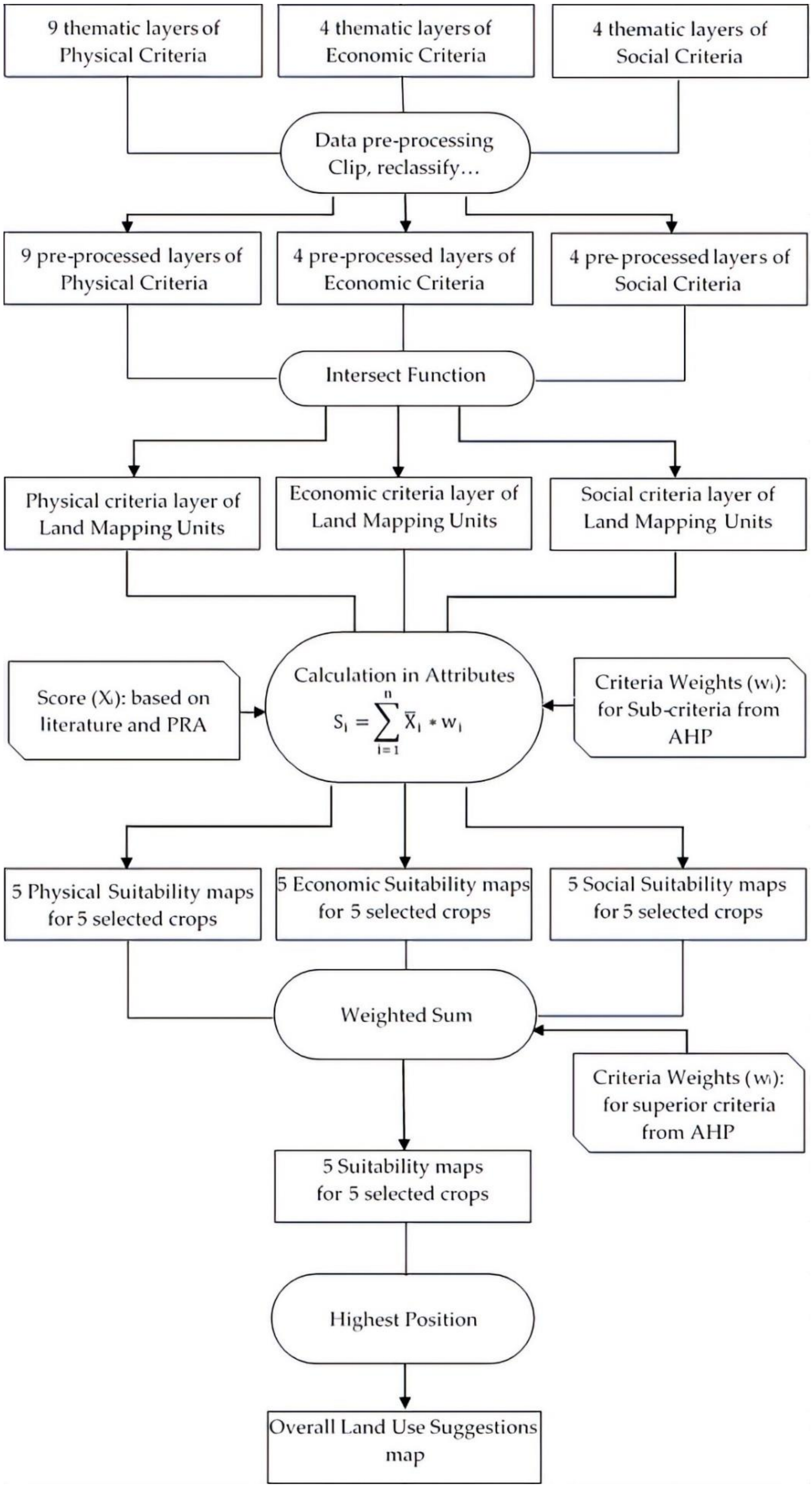

Figure 5.3. Flow chart of GIS – based land evaluation methodology

5.3. Results

5.3.1. Selected crops for land suitability evaluation

The group discussions led to the assumption that seven main crops are currently being cultivated in A Luoi district: acacia *(Acacia spp.)*, cassava *(Manihot esculenta)*, rice *(Oryza sativa)*, rubber *(Hevea brasiliensis)*, banana *(Musa spp.)*, coffee *(Coffea canephora)*, and different vegetables.

The pairwise comparison for the selection of land use type was conducted in-group discussions with 25 participants from different backgrounds. The result (Table 5.7) indicates that acacia, cassava, rice, rubber, and banana represent the most promising LUTs, and will hence be evaluated in this research.

Table 5.7. Final ranking of crops in A Luoi district for land suitability evaluation derived from pairwise comparison of experts.

	Physical conditions	**Economic conditions**	**Social conditions**	**Total**	**Final rank**
Acacia	0.136	0.172	0.045	0.353	1
Cassava	0.081	0.142	0.029	0.252	2
Rice	0.048	0.096	0.025	0.168	3
Rubber	0.032	0.043	0.008	0.084	4
Banana	0.027	0.036	0.007	0.070	5
Vegetables	0.016	0.021	0.006	0.044	6
Coffee	0.012	0.014	0.003	0.030	7

5.3.2. Characteristics of physical, economic and social of LMUs

The LMUs map contained 987 land units for different physical, economic, and social criteria.

5.3.2.1. Layers of physical characteristics

There are nine physical characteristics layers present in Figure 5.4.

* Slope: 13,500 hectares of the total study area, mainly located in the center of the valley, show moderate slope levels between 0 and 7.9 degrees. The slope level rises with increasing distance from the valley and the highest slope levels of more than 25 degrees are found along the mountainsides in the western part of the district.

* Elevation: The center of the valley and the eastern part of the district exhibit a low elevation level, with approximately 2000 hectares underneath the elevation thresholds of 500 meters. Nearly 30,000 hectares of the studied area show elevation levels between 501 and 750 meters. The remaining parts, especially in the west, mostly exceed an elevation of 1000 meters above sea level.

* Soil type: The acrisol represents the only prevalent reference soil group within the research area. Acrisols (ferralic) cover the largest parts with 43,500 hectares and are scattered all over the district. Acrisols (arenic) occupy the second largest area with a size of 8700 hectares in the central east of the district. Acrisols (hyperdystric) can be exclusively found in the valley intersecting the district and Acrisols (humic) exclusively occur in small patches, mainly in the north-west of the district.

* Soil texture: Pure loam occupies the largest extent with an overall area of around 40,400 hectares. Clay loam is present on only 3500 hectares in the north and silt loam occupies 13,600 hectares in the valley and in the eastern parts of the district.

* Soil depth: A soil depth of more than 100 cm is prevalent on nearly 30,000 hectares, followed by a soil depth of 70–100 cm occupying about 15,000 hectares. Soil depths of less than 70 cm can be found on only 25% of the evaluated area.

* Soil pH: The soil in the entire area can be referred to as acidic. The soil pH ranges from 3.9 to 4.4. The soil pH of the central district is higher than in the remaining regions.

* Soil total nitrogen: The soil total nitrogen contents in the region vary between 0.06 and 0.12 percent of the soil weight. The lowest soil nitrogen levels can be found in the eastern region of the district, while higher ones can be measured in the central west, in the valley, as well as in the southern part.

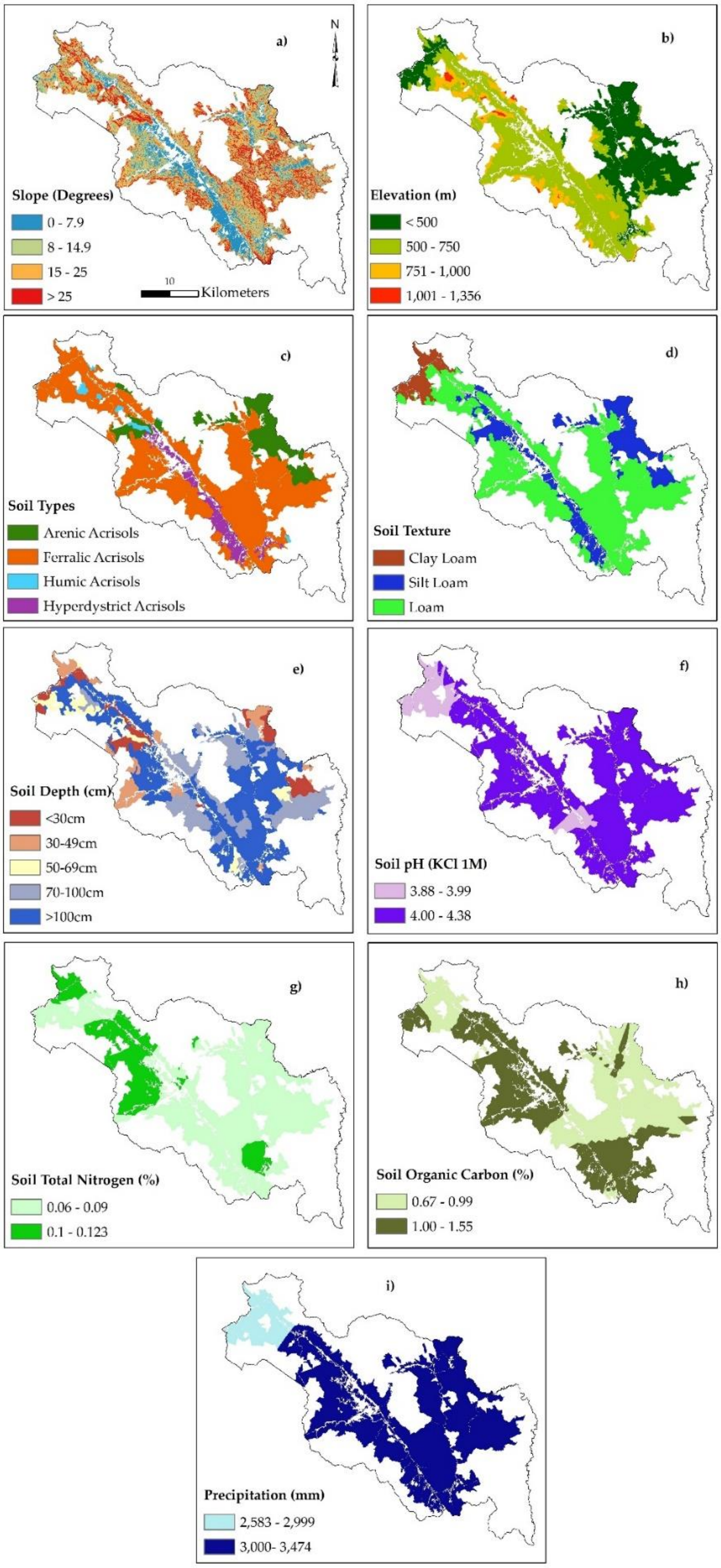

Figure 5.4. Geographic distribution of physical criteria in A Luoi district: a) slope; b) elevation; c) soil types; d) soil texture; e) soil depth; f) pH value; g) soil total nitrogen; h) soil organic carbon; i) annual precipitation.

* Soil organic carbon: The average soil organic carbon contents in the region range between 0.67 and 1.55% of the soil weight. Similar to soil total nitrogen contents, soil organic carbon shows the highest levels in the valley and in the southern part of the district, while the soil organic carbon contents in the eastern part remain low.

* Precipitation: Due to the high mountains in the west, the precipitation in A Luoi district is rather high, varying between 2500 mm and 3500 mm. Rainfall levels reach their maximum in the center of the district.

5.3.2.2. Layers of economic characteristics

There are four economic characteristic of economic layers as show in Figure 5.5.

* Financial ability of the family: This criterion refers to the financial ability of the family to invest in agricultural cultivation. The households in the center of the district are able to cover larger amounts of financial requirements for cropping by their own means.

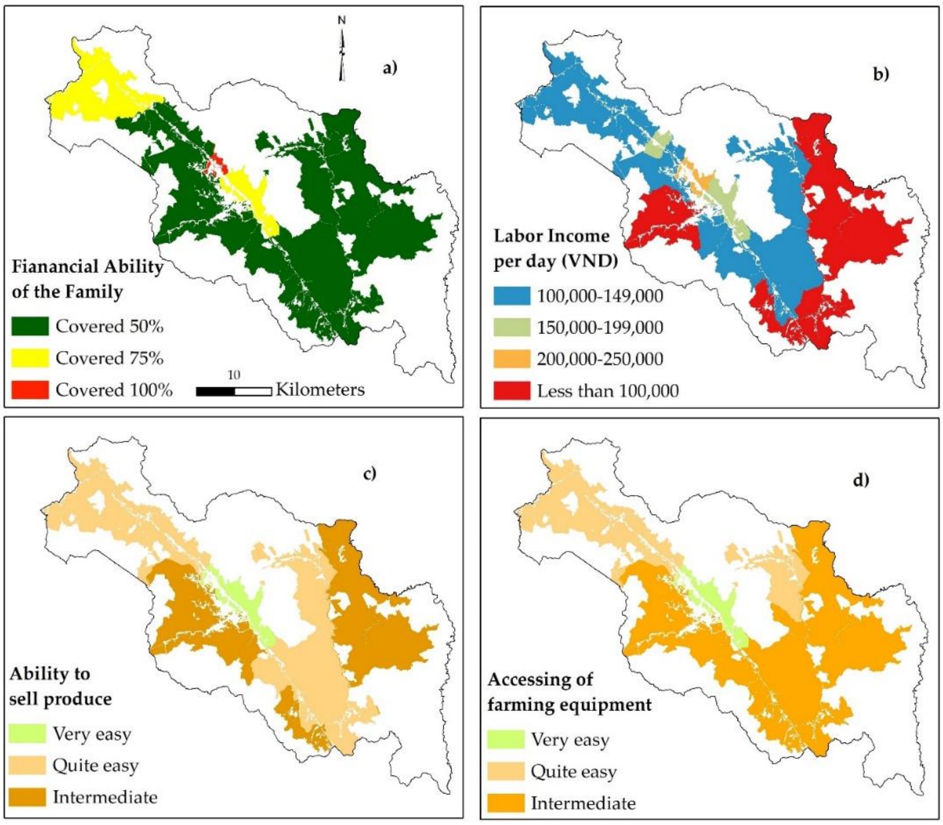

Figure 5.5 Geographic distribution of economic criteria in A Luoi district: a) financial ability of the family; b) labor income per day; c) ability to sell produce; d) accessibility of farming equipment.

* Labor income per day: The criterion describes the daily average income of a farmer who spends one day of work on the respective crop. The labor income per day plays an essential role in commercial LUTs, such as rubber, acacia, and banana. The income of people, who live in the communes that are located in the center of the district and in the lower terrain area, is higher than the labor income of other communes, as these offer other income opportunities. On average, their income amounts to more than 150,000 VND per day. While the labor income in the north was estimated between 100,000 and 149,000 VND per day on average, in the mountainous communes along the southern and eastern district border, labor income falls below the line of 100,000 VND.

* Ability to sell produce: The communes along the main road (national road) can quite easily sell their products. For the mountainous communes, located far away from the main roads, as well as the large rural commune of Huong Nguyen, the selling of produce is more challenging.

* Accessibility of farming equipment: This criterion describes the ability of a farm family to purchase farming equipment. Again, the communes located in favorable areas have better access to the inputs and agricultural machinery than other communes do.

5.3.2.3. Layers of social characteristics

There are four social characteristics layers present in Figure 5.6.

* Farming skills: One of the most challenging issues of farmers in the A Luoi district is the level of farming skills. Farming skills are vital, especially for agricultural LUTs, like rubber and banana. In general, most local farmers practice agriculture based on their experiences.

* Labor force availability: This criterion refers to the potential agricultural labor force that each household in the commune can provide. The local people in the central area have other income opportunities apart from agriculture, as already described in the context of labor income per day. As a result, the labor force that is available for agricultural production is lower than in rural and mountainous communes.

* Access to information: The information regarding agricultural practices and technologies is crucial for agricultural production, especially for commercial LUTs. According to the experts, only the inhabitants of A Luoi Town, which is characterized by favorable infrastructural conditions, are, on average, highly informed regarding new developments in the sector. Other communes in the valley and around A Luoi Town, as well as Hong Ha commune, are assigned a medium level of information, while the mountainous communes show a low level of information accessibility.

* Poverty rate: The criterion estimates the share of commune's inhabitants living below the poverty line, which is defined at 700,000 VND per month. Around 37% of all households in the A Luoi district live below the poverty line. A low poverty rate is assigned to the least rural communes, as A Luoi Town and the adjacent communes in the valley. A high population living below the defined poverty line characterizes the remaining regions.

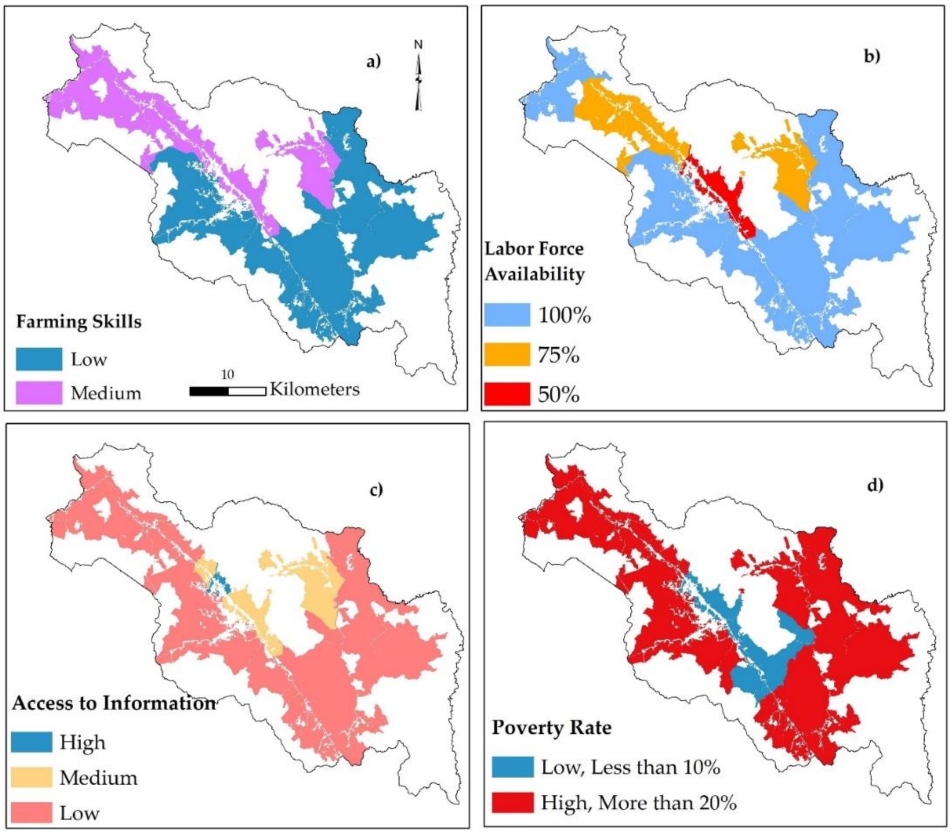

Figure 5.6. Geographic distribution of social criteria in A Luoi district: a) level of faming skills; b) labor force availability; c) access in information; d) poverty rate.

5.3.3. Criteria weights and scores

The criteria weighting shows differences in the level of importance of each criterion (or sub-criterion) on the different LUTs (Table 5.8).

Table 5.8. Weights of overall Criteria (bolt number) and Sub-Criteria based on AHP.

	(Sub-)Criterion / LUTs	Rice		Cassava		Acacia		Rubber		Banana	
Physical Criteria	Soil type		0.18		0.13		0.17		0.13		0.14
	Slope		0.06		0.06		0.11		0.07		0.05
	Soil texture		0.15		0.07		0.08		0.08		0.10
	Precipitation		0.14		0.06		0.05		0.05		0.04
	Soil organic carbon	**0.36**	0.17	**0.32**	0.24	**0.28**	0.17	**0.25**	0.26	**0.27**	0.27
	Soil total nitrogen		0.13		0.22		0.17		0.19		0.22
	Soil pH		0.09		0.07		0.08		0.05		0.05
	Elevation		0.04		0.05		0.06		0.05		0.05
	Soil depth		0.04		0.09		0.12		0.13		0.09
Economic Criteria	Labor income per day		0.18		0.33		0.24		0.18		0.13
	Financial ability of the family		0.25		0.32		0.17		0.20		0.15
	Accessibility of farming equipment	**0.18**	0.41	**0.38**	0.21	**0.55**	0.08	**0.58**	0.10	**0.59**	0.09
	Ability to sell produce		0.16		0.13		0.51		0.51		0.62
Social Criteria	Labor force availability		0.45		0.33		0.32		0.18		0.28
	Access to information	**0.47**	0.20	**0.30**	0.17	**0.17**	0.23	**0.18**	0.19	**0.14**	0.15
	Poverty rate		0.23		0.38		0.36		0.41		0.30
	Farming skills		0.11		0.11		0.08		0.22		0.27

In general, the economic aspects play an essential role in commercial LUTs, such as rubber, acacia, and banana. Hence, on the highest level of the hierarchy, the overall economic criterion was assigned a considerably higher priority for the commercial crops (all > 0.5) than for rice and cassava. As opposed to this, physical and social criteria seem to be more critical for rice and cassava LUTs than the economic criteria. Moreover, each sub-criterion has a different impact on the particular LUT. For example, with respect to physical conditions, soil quality criteria generally have a stronger influence than terrain criteria. Regarding economic criteria, the commercial agricultural LUTs (acacia, rubber, and banana) are mainly influenced by criteria that are associated with the market.

The scoring of the attribute of criteria (Table 5.9) is the assessment of the LUTs suitability with the particular attribute of each sub-criteria related to physical, economic, and social conditions. Regarding the criteria scoring, the attributes of all criteria were rated for each LUT with respect to the specific LUT requirements. For physical criteria, the scoring was carried out based on the PRA surveys as well as on literature that Sys et al. (1993) [22] provided. The results indicate that the PRA scoring and literature scoring approach show similarities, but differ in their magnitude. Concerning physical criteria, low pH values, high levels of slope, as well as low soil fertility in the region are a limiting factor for all kinds of agricultural land use. On the contrary, the main soil texture attributes and precipitation levels are favorable regarding the majority of LUTs. With respect to economic criteria, low criteria levels are assigned to most commercial LUTs. Regarding the prevailing social conditions within the study area, the differences between the commercial LUTs, except for acacia and the non-commercial LUTs can be observed. A low level of farming skills and information access, as well as a high poverty rate, result in a more negative score for commercial crops. In general, the remaining LUTs are more resilient to unfavorable social circumstances.

Table 5.9. Scores based on PRA and literature scoring approach.

	PRA Scoring					Literature Scoring			
Criterion and Level	**Rice**	**Cassava**	**Acacia**	**Rubber**	**Banana**	**Rice**	**Cassava**	**Rubber**	**Banana**
Soil depth (cm)									
< 30 cm	7.20	4.79	4.22	3.23	3.00	4	3.5	3.5	3.5
30 - 49 cm	9.00	7.45	5.00	3.47	4.79	5.5	3.5	3.5	5.5
50 - 69 cm	6.43	7.45	7.00	5.78	6.85	6.5	5.5	5.5	6.5
70 - 100 cm	6.93	5.44	7.61	7.80	7.45	7	6.5	5.5	7.5
> 100 cm	7.00	5.00	7.61	8.08	8.45	8	8	7	8.5
Soil texture									
Silt loam	6.50	7.30	7.61	7.52	7.30	8.5	7.5	7.5	8.5
Loam	7.33	6.85	7.20	6.83	7.94	7.5	7.5	7.5	7.5
Clay loam	6.14	4.79	6.17	5.78	7.45	8.5	7.5	8.5	8.5
Elevation (m)									

< 500	9.00	7.94	8.63	8.38	8.45				
501 - 750	7.20	7.00	9.00	7.26	7.94	No Information			
751 - 1000	5.59	6.44	8.28	6.36	5.92				
> 1000	3.76	5.00	5.92	4.32	3.87				
Slope (°)									
0 – 7.9	8.20	9.00	6.80	8.38	8.45	7	7	7	7
8 -14.9	4.72	7.00	8.63	7.26	7.45	5.5	5.5	5.5	5.5
15 - 25	3.58	5.72	7.61	5.47	4.66	3.5	4.5	4.5	4.5
> 25	3.09	3.44	4.90	3.12	3.21	3.5	3.5	3.5	3.5
Soil total nitrogen (%)									
< 0.1	4.72	5.44	5.92	3.73	5.44	No Information			
0.1 - 0.15	5.81	6.30	7.61	5.50	5.79				
Soil organic carbon (%)									
0.5 – 0.99	5.28	7.00	6.90	4.76	5.44	6	6.5	8	6
1.0 - 1.5	6.43	7.94	7.61	6.59	7.45	6.5	7.5	8	6.5
Soil pH									
3.5 - 3.99	3.76	4.79	6.90	4.65	4.40	4.5	4.5	4.5	4.5
4.0 - 4.5	5.97	6.44	7.61	6.06	5.92	4.5	4.5	5.5	4.5
Soil type									
Acrisol (Humic)	6.13	6.85	7.61	6.67	7.45				
Acrisol (Arenic)	5.28	6.44	7.30	6.36	7.00	No Information			
Acrisol (Hyperdystric)	6.67	6.85	4.72	6.36	7.94				
Acrisol (Ferralic)	5.18	7.00	6.90	6.83	5.44				
Precipitation (mm/year)									
2500 - 2999	7.26	7.30	8.28	7.52	7.00	6.5	6.5	8.5	8.5
3000 - 3500	6.43	7.30	7.30	6.36	5.92	6.5	6.5	8.5	8.5
Labor income per day (VND)*									
200,000 – 250,000	8.68	8.63	9.00	8.08	8.28				
150,000 – 199,000	8.68	7.61	8.14	6.36	7.00	No Information			
100,000 – 149,000	6.36	5.92	6.43	4.02	4.86				
< 100,000	4.53	4.22	5.35	3.00	3.27				
Financial ability of the family									
Covered 100%	9.00	9.00	9.00	9.00	9.00				
Covered 75%	8.08	7.30	8.14	7.52	7.50	No Information			
Covered 50%	6.92	5.59	7.24	6.06	4.92				
Accessibility of farming equipment									
Very easy	9.00	9.00	9.00	9.00	9.00				
Quite easy	7.80	8.63	8.56	7.00	7.50	No Information			
Intermediate	6.06	6.62	6.12	5.25	4.72				
Ability to sell produce									

Very easy	9.00	9.00	9.00	9.00	8.63	
Quite easy	8.68	7.61	9.00	7.00	6.26	No Information
Intermediate	7.17	5.43	7.00	3.92	4.10	
Labor force availability						
100%	9.00	8.45	9.00	9.00	9.00	
75%	7.94	7.00	8.45	7.45	8.45	No Information
50%	5.92	5.92	6.44	5.44	7.45	
Poverty rate						
High (> 20%)	5.92	5.44	5.44	3.41	3.41	No Information
Low (< 10%)	9.00	9.00	9.00	7.00	7.94	
Farming skills						
Medium	7.45	7.45	7.94	7.00	6.44	No Information
Low	5.92	5.92	6.44	3.87	3.87	
Access to information						
High	9.00	9.00	9.00	9.00	8.45	
Medium	6.85	7.45	7.45	6.44	7.00	No Information
Low	5.44	5.92	5.21	3.87	4.79	

[*]1 euro equal to 27,000 VND (2018)

5.3.4. Land suitability for selected land use type

5.3.4.1. Rice

4,139 hectares of the study area are suitable for rice production, with a suitability index of 6.41 for the least suitable and 7.88 for the most suitable areas. Most suitable areas for this kind of land use are located in the center of the valley and the north of the district. In the south, some potential areas with a comparably low suitability index exist around Huong Lam.

5.3.4.2. Cassava

Cassava represents a LUT of high potential in A Luoi district with 39,027 hectares of potential agricultural areas. The suitability index varies from 6.29 to 7.92. Within most land units, cassava cropping only faces slight limitations. Therefore, no significant unfavorable conditions concerning either the physical, economic, or social criteria exist. The central region represents the most suitable area, while the eastern and western parts only show low to medium suitability levels.

5.3.4.3. Acacia

Even though soil depth significantly limits the acacia LUT, this kind of tree still shows a high potential. In total, 21,082 hectares are suitable for acacia with suitability indices that range from 5.96 to 8.42. The areas with a high suitability index (more than 7.0) account for 17,500 hectares, which equal 83% of the entire suitable areas. The most suitable land units are located around A Luoi Town stretching out into the southern and northern direction of the valley. The communes along the western and eastern district border, on the contrary, were entirely evaluated as unsuitable for this LUT.

5.3.4.4. Banana

Banana is a commercial LUT, which became more popular in A Luoi district in recent years. The calculated suitability indices for banana vary between 7.5 and 8.07, with a mean of 7.70. Most of the suitable areas are located in the center of the district with the highest suitability in the northern and the lowest in the southern parts. In total, 1,584 hectares are suitable for banana cultivation.

5.3.4.5. Rubber

The area that is suitable for rubber cultivation is not significant, as it only amounts to 120 hectares in the center of the district. Suitability indices between 7.51 and 8.09 were assigned to this area.

5.3.4.6. Overall land use suggestions

The most suitable land use type was determined for each land unit (Figure 5.8) based on the suitability maps for each land use type (Figure 5.7). The results show that rice production could be carried out in the areas in the north-western communes, such as Hong Bac, Bac Son, Hong Trung, Hong Van, and Hong Thuy on of 1,388 hectares. The western, southern, and eastern parts are most the suitable for cassava cultivation with a large area of 23,835 hectares. The suitable areas for acacia account for 18,438 hectares, and they expand from the northern communes along the valley towards the southern and eastern parts of A Luoi district. The area for rubber cultivation type is small, with only five hectares in A Luoi Town. Small land units, summing up to the extent of 437 hectares in A Luoi Town and along the main road are suitable for banana LUT.

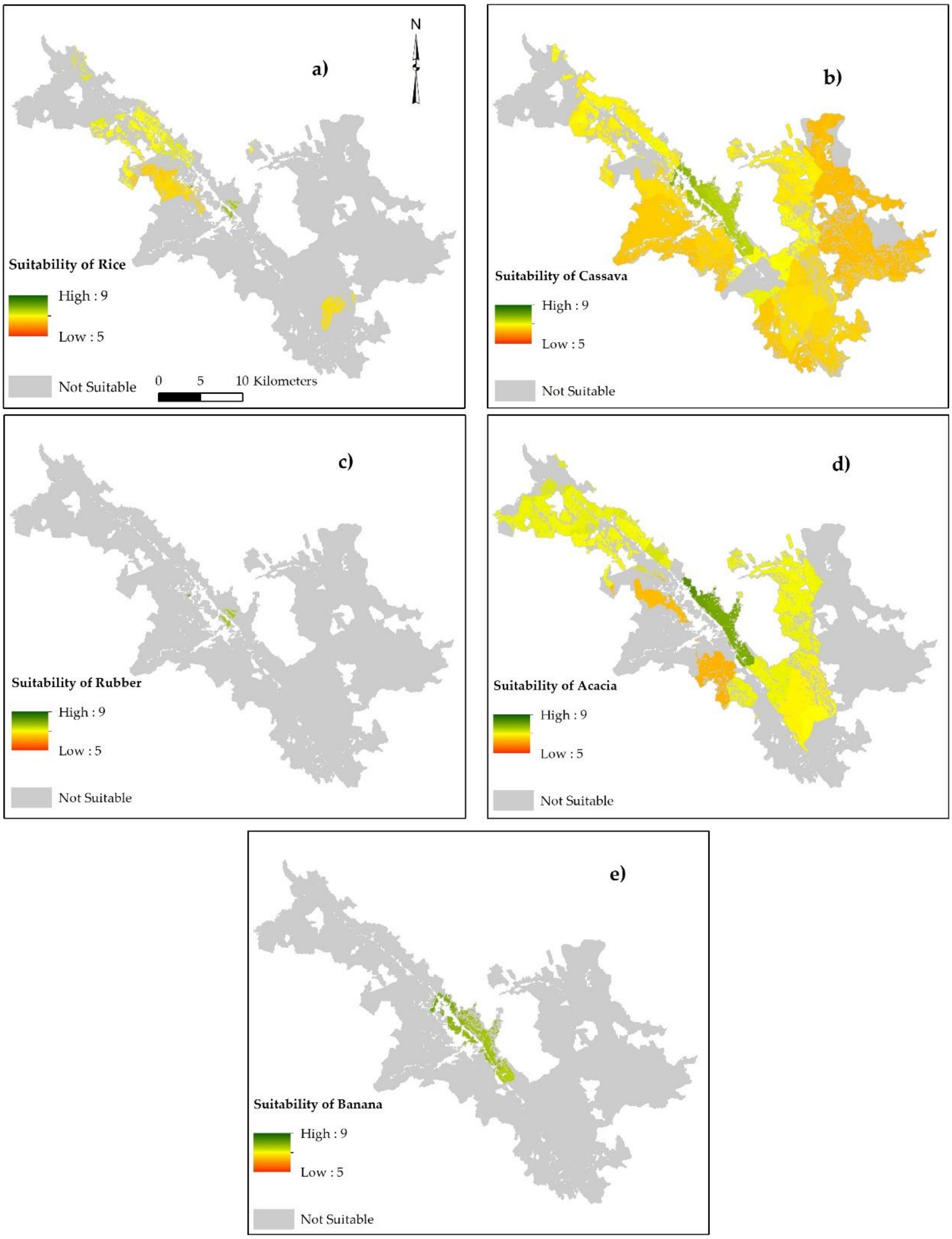

Figure 5.7. Land suitability for selected land use types: (**a**) suitability of rice; (**b**) suitability of cassava; (**c**) suitability of rubber; (**d**) suitability of acacia, and, (**e**) suitability of banana.

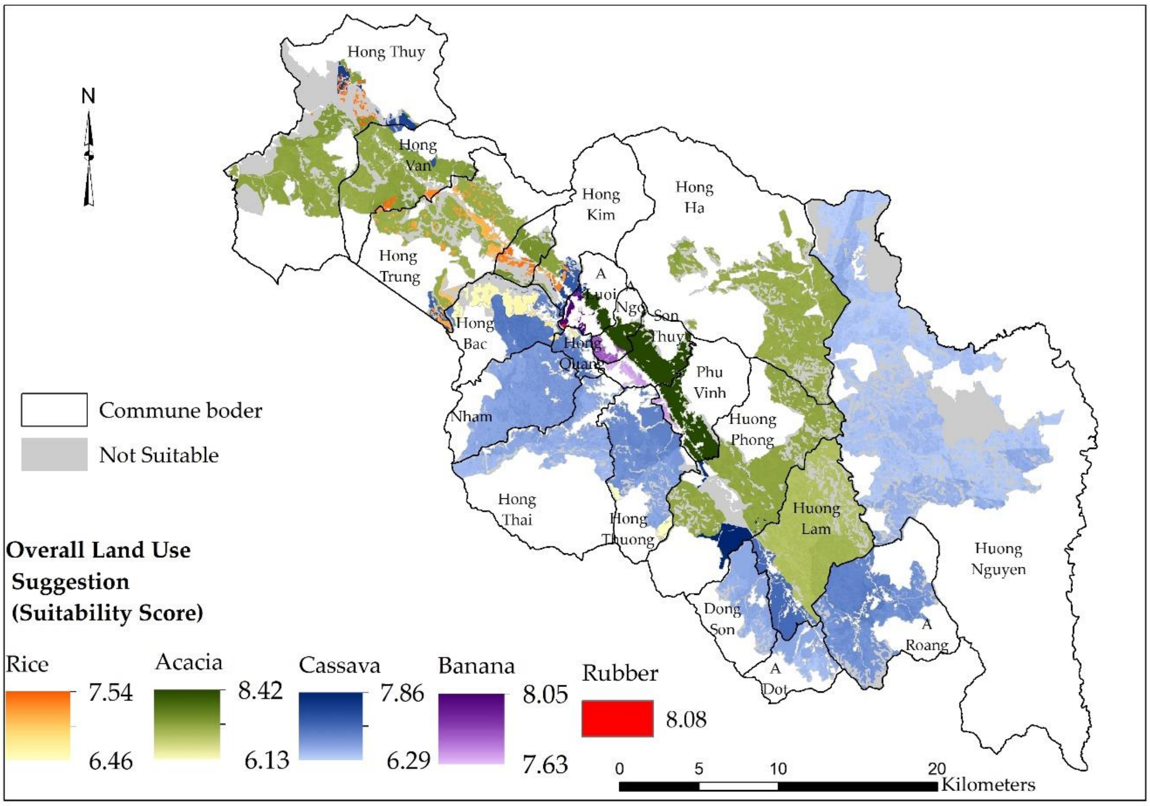

Figure 5.8. Overall land suitability of selected land use types for entire district

5.4. Discussions

5.4.1. Land suitability evaluation methodology

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 Vietnamese uplands, social and economic characteristics have a significant impact on agricultural land use [62]. The MCDA procedure allowed for the integration of physical, economic, and social criteria, as well as the involvement of local experts' judgments. However, these judgments can be highly variable in space and time, which thus leads to a trade-off between local knowledge involvement and objectivity. Moreover, it has limitations of dependency among criteria [63]. Zolekar & Bhagat (2015) [57] make use of correlation analysis to demarcate the most determining criteria for agricultural land use and to eliminate the interdependent ones, which would have been an adequate option to improve the data base.

The use of a Geographic Information System proved to be highly useful in the context of land suitability evaluation, as it facilitates the geographic assignment of criteria to land units. For physical criteria, random sampling and interpolation proved to be an adequate approach to represent the physical conditions in the area [42]. However, the Boolean approach still has limitations on the ability to express the transitional or continuous variation in geographical features [64]. To reduce this limitation, Fuzzy set theory [65] with partial membership function could be used as an appropriate solution [66,67]. With regard to the economic and social criteria, it must be noted that the community-wise assignment of characteristics leads to oversimplification, as socio-economic traits can differ considerably, even within communities. For a small-scale and more appropriate observation, a household survey on socio-economic factors regarding agricultural land use practices would be required. However, as stated by Yen et al. (2013) [62], a more complex approach to land suitability evaluation requires high quality data and sufficient resources to acquire such data.

This study indicates that the exclusive procurement of scoring values from Sys et al. (1993) [22] cannot draw a holistic picture of the local conditions. The land suitability evaluation that is based on the PRA survey differed considerably from this approach, particularly in the evaluation of the commercial crops rubber and banana. According to the guideline of Sys et al. (1993) [22], most agricultural land of A Luoi district would be unsuitable for crop production, due to the soil being very acidic and the steep terrain. However, diverse agricultural land use is taking place in the research area. This finding leads to the conclusion that site-specific knowledge regarding local characteristics cannot be captured by universally applicable literature. Therefore, this study suggests the integration of scientifically grounded literature on crop requirements and local knowledge in the form of a scoring through PRA methods.

5.4.2. Limiting factors for agricultural production

Many environmental, economic, and social conditions of A Luoi district are unfavorable for agricultural production. Physical criteria, such as steep terrain, soil acidity, and low soil nitrogen are the main restrictions for agricultural cultivation, especially for commercial crops, like rubber and banana. Serious erosion rates, population pressure, and shortened fallow periods have an additional negative effect on sustainable cultivation [68,69].

Unfavorable economic conditions are mainly prevalent in the remote areas of the study area due to infrastructural and physical limitations [70], which particularly affect the production of commercial crops. An essential requirement for this kind of land use is the long-term financial ability. The cultivation of perennial commercial crops requires significant investments during the early period of crop production, with expected benefits at a later stage [71] within the last years of the life span of perennial crops, the productivity and quality of the agricultural product will decline significantly, leading to economic risks for the local farmers [72]. Hence, from an economic viewpoint, the accessible and central municipalities are the most suitable for agricultural land use.

The evaluated crops are from a social perspective most suitable in the lowland where the lowest poverty rates, sufficient access to information, and a higher level of farming skills are prevalent. These social conditions are vital for the production of rubber and banana. For instance, the plantation of rubber trees, the harvest of latex, and the manufacturing of a transportable rubber product demand a considerable degree of technological knowledge [73,74]. In comparison to cassava and upland rice, the knowledge base among farmers regarding new commercial crops is still limited [72].

5.4.3. Future perspective on agriculture in A Luoi district

Significant changes in investment, household income, and policies have occurred in the Vietnamese agricultural sector within the last decades [75–77]. Traditional agricultural practices are gradually replaced by rather market-oriented food and commodity production [68]. However, agricultural production in Vietnam still faces many serious challenges, such as marker price volatility, financial resources, and farming skills [78]. These difficulties are more serious in the upland regions, where ethnic people groups represent the majority of the population [62].

In the following, the land evaluation results will be discussed with respect to the land use development plan for A Luoi district until 2030 [79]. Crop diversification is found to stabilize incomes and enhance resilience [80]. A mixed agricultural land use planning involving commercial and non-commercial crops is a promising land use scheme for A Luoi district. Rubber, banana, and rice should exclusively be cultivated in the flat land, while acacia and cassava should expand in the rural area and remote communes.

According to the land use planning of A Luoi district, rice expansion is planned on 2,300 to 2,500 hectares in all communes, specifically in Huong Phong, Hong Ha, and Huong Nguyen. Nonetheless, rice cultivation will not be possible in these areas without the implementation of appropriate coping strategies that are aimed at an enhanced level of soil nitrogen and carbon. An expansion of rice fields towards Hong Bac and Hong Trung, represents an optional strategy.

Acacia is an exceptional commercial land use type, for which an expansion of the cultivation area is encouraged and social acceptance is high. The expansion should especially be carried out on bared lands, which is in line with the outcomes of the land suitability evaluation. However, the intended conversion of current coffee zones to acacia plantations might be challenging, as this region is not suitable for any of the evaluated land use types.

Cassava, similarly to acacia, can flexibly be planted within many communes, even in remote areas. Intercropping could be applied for this kind of land use as well as acacia to supply the numerous food factories in Hue and Da Nang city. It also helps local farmers to increase their income and savings through the reduction of fertilizers.

Regarding banana, the district plans to expand up to 200 to 250 hectares in some communes in the northern part of the district and A Luoi Town. Potential banana planting in A Luoi commune is possible based on the performed land suitability evaluation. Communes that are designated for banana production in the future land use plan are less suitable when compared to the central valley communes of A Ngo, Son Thuy, and Phu Vinh.

Concerning rubber production, the future-zoning plan for A Luoi district intends to expand rubber plantations on 1,000 to 1500 hectares in Phu Vinh and Son Thuy communes and to maintain current rubber plantations. The findings of the land suitability evaluation suggest rubber expansion within Son Thuy commune, even though this area seems more suitable for acacia. The current rubber plantation zones (in Hong Ha, Nham commune) are unsuitable for rubber products according to the land suitability evaluation. This fact is in line with statements of locals during group discussions who mention that scattered rubber trees are only planted in these areas as a consequence of rubber subsidization programs, and are hence not sustainable on a long-term basis.

5.5. Conclusions

This research is the first GIS-based multi-criteria land suitability evaluation based on physical, economic, and social conditions, conducted in a hilly district of Central Vietnam. It provides a framework for land evaluation relevant to stakeholders on the district level of Vietnam. Moreover, land suitability evaluation can function as a vital planning tool to rationally assess sustainable agricultural practices for a region and enable the prevention of a trial and error process in agricultural land use planning. Therefore, land suitability evaluation should be a mandatory step before implementing any specific land use, especially in the agricultural sector.

In the frame of this research, it became apparent that future land use practices envisaged by planning authorities do not always coincide with the expectation of land user, scientists, and even different departments in the government system. The promotion of commercial crops, like rubber and banana in A Luoi district, needs careful consideration as major constraints, especially on the economic level, prevail within the research area.

5.6. References

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Chapter 6. Summary findings, contributions, limitations, and recommendations

6.1. Summary

In this thesis, the three main objectives of soil quality indicators testing, soil properties mapping, and land evaluation have been accomplished. Below the thesis is summarized in the form of it goals:

a) The soil quality indicators of agricultural land in A Luoi district were analyzed. These indicators indicate that the soil quality of the agricultural land in the district are at low or medium levels compared to other regions of Vietnam.

b) Soil quality indicators were significantly influenced by land use types. Arable land use type (Rice and cassava) has the most impact on soil properties. The soil properties of the top layer is better than the lower soil layer.

c) No significant difference was found between soil organic carbon and topographic aspect (at a confidence level of 95%).

d) Regrading soil property mapping, the interpolated soil organic carbon and soil total nitrogen maps show that ordinary kriging is more accurate than regression kriging when using the three auxiliary variables of land use type, transformed soil adjusted vegetation index, and topographic wetness index. The weak correlation between the auxiliary variables and the predicted variables is mainly due to the low accuracy of the regression kriging method. However, the RK method is better than the OK method for soil pH mapping.

e) In total, 987 land units were created from nine physical criteria, four economic criteria, and four social criteria and they were chosen for the agricultural land evaluation.

f) The group discussions show that currently seven main land use types are being cultivated in A Luoi district. Among them, five land use types (rice, cassava, acacia, banana, and rubber) are potential crops in A Luoi district based on physical, economic, and social characteristics of the land map units.

g) In general, the overall economic criterion was assigned a considerably higher priority for the commercial crops (banana, rubber, and acacia). For the remaining crops (cassava and rice), physical and social criteria seemed to play a more relevant role. Regrading physical criteria, soil organic carbon, soil total nitrogen, and soil type were considered crucial determinants for all crops. The priority of economic sub-criteria strongly depends on the respective land use type. While labor income per day constitutes the most important sub-criterion for rice cropping, the financial ability of the family is most relevant for cassava production, and the ability to sell produce is the most determining factor for acacia, rubber, and banana cultivation. Regarding social sub-criteria, labor force availability ranks highest for rice farming while the poverty rate has the highest impact on the cultivation of all other crops.

h) There are 4,139 hectares suitable for rice production, especially in the northern and central regions of district. A Luoi district can be referred to as moderately suitable for both cassava and acacia crops, with 39,027 ha and 21,082 ha available, respectively. Some land units around the A Luoi Town and Son Thuy communes are suitable for rubber plantations with 120 hectares, while 1,584 ha are suitable for banana production.

i) An agricultural land use type proposal based on the land suitability of five crops was made created, which we called the suitability index. This means that if more than of one crop is suitable to the same land unit, and then the crop with the highest suitability index value will be chosen. The area in which rice represents the crop of choice is comparably limited with an extent of 1,388 ha. With an area of 23,835 ha, cassava shows the highest suitability indices compared to all other land use options. Acacia is characterized by a relatively high suitability in the largest parts of the district, amounting to a total extent of 18,438 hectares. Small land units in A Luoi Town and the neighboring communes along the main road are most suitable for banana cropping, summing up to an extent of 437 hectares. Meanwhile, only 5 hectares were suitable for rubber plantations.

k) From a methodological viewpoint, even though most studies rely on the literature for the assessment of crop suitability, we suggest an integration of relevant literature and local knowledge, which both represent reasonable information sources.

6.2. Contributions

a) This study is the first systematic research project focused on soil quality, soil mapping, and land evaluation for agricultural development in the hilly regions of central Vietnam.

b) Chapter 3 provided an overview about the soil quality of the agricultural areas in A Luoi district of central Vietnam. The updated information about soil organic carbon, soil total nitrogen, and soil acidity are basic information for further research relevant to agricultural development in this district.

c) Chapter 4 provided a framework for soil quality indicator mapping based on regression kriging. Even though the land use type, transformed soil adjusted vegetation index, and topographic wetness index did not significantly improve the accuracy of the regression kriging method, the research proved how selected environmental variables affect soil quality indicators. With this chapter, researchers avoid the wasted time expense of determining certain auxiliary variables.

d) Chapter 5 provided clear evidence regarding the advantages of combining local and scientific knowledge for land evaluation. The results of this study provide reasonable and effective agricultural land use scenarios for local policy makers.

6.3. Limitations and recommendation

a) For soil quality indices, both the number of soil samples and the number of soil quality indicators need to be increased to increase precision.

b) A decrease in distances between the soil samples could produce better soil quality mapping results. Moreover, for the regression kriging method, using more auxiliary variables could also improve the accuracy.

c) Regarding the land suitability evaluation, adding more physical criteria (e.g. potassium content, phosphorus content, soil moisture), social criteria (e.g. number of skilled workers, characteristics of ethnic minorities), and economic criteria (e.g. fluctuations in prices, interest rates) could produce better results. Participants in the land assessment process also need to participate at a more detailed level. The contributions of farmers should be implemented at the land unit level in each village and commune.

d) Through the course of this research, it became apparent that land use practices envisaged by planning authorities do not always coincide with the actually evaluated suitability of the respective land unit. Therefore, local policy makers should use land evaluation as an indispensable tool before implementing any agricultural land use planning. Promotion of commercial crops or support programs for agricultural and rural development need to be undertaken cautiously based on multi-stakeholder consultation.

Appendix

ID	Sample_Name	X	Y	Landusecod	SOC_Top	SOC_Sub	STN_Top	STN_Sub	pH_Top	pH_Sub	TWI	TSAVI	Sampletype
1	SX13Hong Ha	1802514	750746	AL	2.1	1.58	0.09	0.07	4.09	4.16	9.51	0.258396	Validation
2	LN4Hong Ha	1804559	744509	NF	1.31	0.95	0.1	0.09	4.15	4.17	9.24	0.28784	Interpolation
3	LN32Son Thuy	1799187	741582	NF	1.37	0.79	0.12	0.11	4.15	4.18	8.38	0.307128	Interpolation
4	SX43Hong Ha	1802713	751427	AL	1.47	0.47	0.11	0.08	4.13	4.2	13.71	0.024248	Validation
5	LN24Hong Ha	1802022	754393	PF	1.31	0.53	0.1	0.09	4.26	4.31	9.16	0.234312	Interpolation
6	LN19Hong Ha	1801756	751437	PF	1.58	0.74	0.1	0.08	4.1	4.09	7.72	0.322929	Interpolation
7	SX14Huong Nguyen	1803681	753966	AL	1.05	0.32	0.08	0.07	4.1	4.36	11.12	0.497294	Validation
8	LN46Hong Ha	1801500	749710	NF	1.05	0.68	0.09	0.07	4.09	4.11	9.48	0.426921	Interpolation
9	LN20Huong Nguyen	1804193	753659	PF	0.79	0.26	0.07	0.07	4.08	4.11	7.11	0.384511	Interpolation
10	LN48Hong Ha	1800129	750612	NF	1.31	0.74	0.06	0.05	4.11	4.14	7.92	0.482296	Interpolation
11	LN13Huong Nguyen	1800887	758109	NF	1.05	0.26	0.05	0.04	4.2	4.3	9.75	0.381279	Interpolation
12	LN12Huong Nguyen	1798602	760366	NF	1.58	0.78	0.06	0.06	4.27	4.29	13.71	0.368592	Interpolation
13	LN58Hong Ha	1797635	750338	NF	0.53	0.37	0.05	0.05	3.91	4.07	10.9	0.132809	Validation
14	LK16Huong Nguyen	1805203	755185	PF	1.05	0.94	0.07	0.07	4.12	4.14	10.76	0.349973	Interpolation
15	SX19Huong Nguyen	1799804	754158	AL	1.21	0.53	0.07	0.05	4.19	4.23	12	0.364046	Interpolation
16	SX18Huong Nguyen	1800738	754913	AL	1.16	0.88	0.06	0.06	4.16	4.23	9.09	0.421019	Interpolation
17	SX9Hong Ha	1803880	751253	AL	1	0.63	0.21	0.14	4.15	4.25	9.04	0.323797	Interpolation
18	LN3Huong Nguyen	1800734	756441	NF	2.89	0.73	0.07	0.06	4.15	4.15	7.91	0.243202	Interpolation
19	LN5Huong Nguyen	1806936	755000	NF	1.52	0.26	0.07	0.07	4.21	4.23	11.59	0.269005	Interpolation
20	LK6Hong Ha	1803214	749492	PF	1.57	0.7	0.09	0.06	4.19	4.25	11.94	0.127883	Interpolation
21	LN14Huong Nguyen	1798500	757500	NF	0.42	0.05	0.07	0.04	4.18	4.2	9.34	0.320007	Interpolation
22	SX12Hong Thuy	1809070	717031	AL	1.28	1.1	0.09	0.07	4	3.97	8.84	0.36288	Interpolation
23	SX42Bac Son	1805079	735403	AL	1.63	1.47	0.12	0.09	4.2	4.22	13.71	0.214367	Interpolation
24	SX31Hong Van	1810138	727409	AL	2.05	1.47	0.1	0.09	4.07	4.11	8.84	0.346501	Interpolation
25	SX8Hong Van	1808576	728703	AL	2.15	1.58	0.1	0.09	4.28	4.36	9.75	0.274975	Validation
26	SX36Hong Bac	1801189	736647	AL	1.52	1.31	0.07	0.06	4.2	4.23	7.1	0.472322	Validation
27	SX33Hong Quang	1799773	737841	AL	1.79	1.37	0.1	0.08	4.68	4.9	13.93	0.420213	Validation

28	LK35TT A Luoi	1800800	736943	GL	1.04	0.74	0.09	0.07	4.54	4.36	10.9	0.150888	Validation
29	SX21Huong Lam	1781675	751720	AL	0.95	0.62	0.1	0.09	4.21	4.2	9.13	0.454162	Validation
30	SX3Hong Trung	1804815	732787	AL	1.2	0.99	0.13	0.1	4.34	4.32	9.1	0.384976	Interpolation
31	SX40Hong Van	1810153	726474	AL	1.31	1.16	0.08	0.1	4.26	4.21	10.85	0.252561	Interpolation
32	SX32Hong Kim	1802396	736470	AL	1.84	1.68	0.13	0.13	4.23	4.25	10.9	0.510408	Validation
33	LK10A Roang	1779759	754717	PF	1.58	1.05	0.1	0.05	4.09	3.96	8.6	0.320413	Interpolation
34	LN34Hong Trung	1807523	729955	PF	1.31	1.05	0.11	0.09	4.08	4.16	10.08	0.364526	Validation
35	LK28Hong Trung	1807425	728320	GL	0.89	0.84	0.12	0.09	4.18	3.8	8.24	0.336018	Interpolation
36	SX16Hong Trung	1806700	731725	AL	1.94	0.63	0.12	0.08	4.5	4.48	9.69	0.24853	Interpolation
37	LK37Hong Trung	1806612	730521	GL	0.95	0.89	0.12	0.09	4.49	4.36	10.09	0.370218	Validation
38	SX7Bac Son	1804380	734477	AL	1.89	1.58	0.12	0.09	4.5	4.53	10.9	0.225448	Interpolation
39	SX24A Roang	1781530	754881	AL	0.84	0.16	0.11	0.08	4.27	3.95	8.27	0.369677	Interpolation
40	LK43Nham	1796282	736019	PF	1.84	1.1	0.14	0.1	4.18	4.15	7.66	0.288505	Interpolation
41	SX26A Roang	1782681	756660	AL	1.16	0.7	0.12	0.09	4.4	4.35	8.81	0.251565	Validation
42	LK44Nham	1795151	735302	GL	0.95	0.7	0.12	0.09	4.02	4.04	8.87	0.180749	Interpolation
43	SX23Nham	1797513	736022	AL	1.03	0.98	0.15	0.1	4.27	4.24	8.24	0.417257	Interpolation
44	LK13Hong Thai	1795762	738506	PF	1.18	0.78	0.09	0.07	4.14	4.2	9.72	0.291116	Validation
45	SX41A Roang	1780153	754828	AL	1.47	1.05	0.1	0.05	4.1	4.11	7.94	0.301136	Interpolation
46	SX11A Dot	1779120	753263	AL	1.24	0.63	0.1	0.06	4.38	4.72	7.8	0.360535	Interpolation
47	LN52Phu Vinh	1792529	745456	PF	1.31	0.74	0.08	0.07	4.07	3.98	9.28	0.411197	Validation
48	LN16Hong Thuy	1810131	720944	NF	0.7	0.33	0.1	0.07	3.72	3.6	9.46	0.44381	Interpolation
49	SX6Hong Thuy	1811011	718263	AL	0.93	0.78	0.11	0.07	4.21	4.37	10.09	0.304789	Validation
50	LK24Hong Thuy	1810367	719346	PF	0.79	0.42	0.1	0.06	3.67	3.61	9.38	0.425582	Validation
51	LN64Huong Phong	1787037	747559	PF	0.53	0.42	0.09	0.07	3.87	3.86	8.87	0.330536	Interpolation
52	LN63Dong Son	1785604	748218	PF	0.61	0.26	0.1	0.08	3.98	3.95	9.61	0.264982	Interpolation
53	LK22Hong Thuy	1808612	720514	PF	1.31	1.05	0.11	0.07	3.82	3.82	9.05	0.31632	Interpolation
54	LK46Hong Trung	1802562	730129	GL	2.47	1.05	0.15	0.11	4.37	4.08	7.86	0.317969	Interpolation
55	SX2Huong Lam	1785044	749219	AL	1.31	1.05	0.1	0.08	4.12	3.95	9.81	0.312061	Interpolation
56	LK48Hong Van	1809046	725247	GL	0.53	0.21	0.1	0.09	3.84	3.87	9.01	0.408817	Interpolation
57	SX1Huong Lam	1784901	749219	AL	1.84	1.04	0.1	0.08	4.11	3.97	13.71	0.293238	Interpolation

58	LN15Hong Thuy	1813635	723572	NF	0.95	0.53	0.05	0.08	4.11	4.09	13.71	0.330196	Interpolation
59	LK9Hong Trung	1803409	731868	GL	0.53	0.26	0.16	0.11	3.72	3.71	9.52	0.300706	Interpolation
60	LK25Hong Thuy	1813484	720898	GL	0.79	0.52	0.19	0.13	4.09	4.04	13.71	0.211002	Interpolation
61	LK8Hong Bac	1803461	732011	GL	0.53	0.41	0.16	0.11	3.67	3.66	9.61	0.326698	Interpolation
62	LN33Hong Bac	1801825	730609	NF	0.89	0.21	0.15	0.11	3.6	3.6	9.01	0.348697	Validation
63	LK7Hong Bac	1802710	733263	GL	0.53	0.26	0.12	0.09	3.75	3.68	13.71	0.090241	Interpolation
64	LN41A Roang	1779907	754363	NF	0.53	0.37	0.1	0.05	3.93	3.98	10.9	0.131239	Interpolation
65	LN56Hong Thuy	1813150	722074	NF	0.89	0.21	0.18	0.15	4	3.96	13.44	0.378976	Interpolation
66	SX30Hong Thuong	1795957	741802	AL	1.31	0.79	0.11	0.1	4.55	4.66	11.07	0.282112	Interpolation
67	SX35Huong Lam	1784300	750021	AL	1.78	1.53	0.11	0.09	4.53	4.42	8.26	0.388012	Interpolation
68	LK20Hong Thuy	1809443	718709	PF	1.78	1.57	0.17	0.07	4.29	4.06	8.9	0.339733	Interpolation
69	LK21Hong Thuy	1808826	718263	PF	2.11	1.41	0.09	0.07	4.27	3.99	9.86	0.225005	Interpolation
70	LN60A Roang	1783609	759732	NF	1.05	0.79	0.05	0.05	4.13	4.2	9.26	0.314692	Interpolation
71	SX10A Dot	1780394	752658	AL	1.4	1.05	0.09	0.06	4.3	4.22	9.51	0.352675	Interpolation
72	LN54Hong Trung	1806829	727500	NF	1.57	1.37	0.13	0.1	3.6	3.67	10.72	0.437116	Interpolation
73	LK5A Roang	1783760	757260	PF	1.63	0.79	0.11	0.08	3.82	4.08	10.44	0.395117	Validation
74	LN43A Roang	1780306	756978	NF	0.53	0.49	0.14	0.1	3.64	3.64	9.47	0.149319	Interpolation
75	LN36Huong Phong	1789500	748364	NF	1.16	0.94	0.06	0.06	3.8	3.8	11.75	0.269024	Interpolation
76	LK38Hong Thai	1791040	730777	GL	1.57	0.92	0.11	0.09	4	4.04	13.71	0.422758	Validation
77	SX4A Dot	1779624	752097	AL	1.63	1.17	0.09	0.06	3.85	3.88	13.71	0.132905	Interpolation
78	LK11Hong Bac	1800480	734628	PF	1.82	1.35	0.12	0.09	3.82	3.82	8.25	0.36899	Interpolation
79	LK39Hong Thai	1790807	730554	GL	0.93	0.74	0.09	0.07	3.91	3.86	10.09	0.159596	Interpolation
80	LK12A Roang	1784500	755393	PF	2.19	1.78	0.19	0.13	3.79	3.84	8.7	0.47711	Interpolation
81	SX22Hong Thai	1796487	738626	AL	1.37	0.94	0.08	0.07	4.31	4.23	8.09	0.327917	Interpolation
82	LK14Nham	1797946	735318	PF	2.36	1.84	0.18	0.1	3.93	3.99	10.44	0.41533	Interpolation
83	LN49Nham	1795557	734246	PF	1.78	1.37	0.15	0.11	3.94	4.04	8.45	0.47207	Interpolation
84	SX25A Roang	1782265	755863	AL	3.02	2.61	0.12	0.09	4.09	4.14	8.04	0.282909	Interpolation
85	LN51Nham	1794911	735930	PF	1.93	0.83	0.1	0.09	3.94	3.9	7.95	0.477331	Interpolation
86	LK40Hong Thai	1791831	732631	GL	0.93	0.74	0.11	0.08	4.09	3.97	9.8	0.321032	Interpolation
87	LN61Nham	1794535	732149	NF	0.83	0.7	0.13	0.09	3.95	3.92	10.37	0.339401	Interpolation

88	SX27Hong Bac	1801358	734087	AL	2.46	1.84	0.11	0.09	4.66	4.45	7.45	0.460267	Interpolation
89	LK31Huong Lam	1791731	753704	GL	1.11	0.56	0.08	0.05	4.13	4.14	13.71	0.324903	Interpolation
90	LN44Hong Van	1808004	723445	NF	1.02	0.57	0.11	0.09	3.89	3.94	10.04	0.424891	Interpolation
91	LK26Huong Lam	1788712	753083	GL	0.82	0.61	0.1	0.08	4.04	4.08	13.19	0.357976	Interpolation
92	LN11Hong Thuy	1815986	720679	NF	1.48	0.93	0.13	0.1	4.34	4.29	9.61	0.241995	Interpolation
93	LN23Son Thuy	1798133	741325	PF	1.37	1.11	0.11	0.1	3.9	4.04	8.54	0.393982	Validation
94	LN35Hong Van	1810950	727421	PF	0.87	0.45	0.1	0.1	4.08	4.09	10.9	0.129198	Validation
95	LN42A Roang	1783500	754129	NF	1.28	0.87	0.14	0.1	4	3.98	9.29	0.326965	Validation
96	LN55Hong Thai	1792511	736500	NF	1.35	0.66	0.11	0.06	4.01	4.09	8.57	0.323638	Interpolation
97	LK30Huong Lam	1791472	752469	GL	1.02	0.41	0.08	0.05	4.11	4.18	9.09	0.447542	Interpolation
98	LN25Hong Bac	1802145	734426	PF	1.35	0.37	0.1	0.08	4.28	4.43	13.71	0.168188	Validation
99	LK19Hong Thuy	1810538	718730	GL	1.52	0.33	0.06	0.05	4.04	3.85	10.7	0.280409	Interpolation
100	LK17Hong Thuy	1810609	717828	PF	1.43	0.93	0.13	0.1	3.94	3.74	8.75	0.401175	Interpolation
101	LK27Hong Thuy	1811273	721578	GL	0.9	0.37	0.05	0.04	3.98	3.83	8.69	0.363352	Validation
102	SX38Huong Lam	1783358	749907	AL	1.31	1.02	0.08	0.07	4	4.04	9.44	0.383183	Interpolation
103	LN53Dong Son	1780787	748871	PF	1.11	0.82	0.13	0.08	4.21	4.34	7.74	0.488338	Interpolation
104	SX28Hong Kim	1802401	736746	AL	1.97	1.43	0.11	0.1	4.29	4.38	8.71	0.362134	Interpolation
105	SX15Hong Thuy	1810699	717475	AL	1.27	0.86	0.13	0.09	4.09	4.01	12.16	0.265715	Interpolation
106	LK15Nham	1796661	735659	PF	1.62	1.11	0.14	0.1	4.14	4.13	9.81	0.257863	Interpolation
107	LK18Hong Thuy	1808012	717337	GL	1.51	1.09	0.1	0.07	4.08	3.95	8.09	0.207716	Interpolation
108	LK1Hong Thuong	1794588	740814	PF	1.3	0.85	0.11	0.09	4.29	4.34	8.05	0.335724	Interpolation
109	LK23Hong Thuy	1809318	716637	GL	1.33	1.06	0.08	0.07	4.02	3.96	12.3	0.37657	Validation
110	LK29Hong Trung	1805793	727289	GL	1.14	0.98	0.13	0.1	4.28	4.19	8.05	0.318367	Interpolation
111	LK2Hong Van	1808745	724233	GL	0.92	0.55	0.1	0.09	3.92	3.93	8.29	0.302921	Validation
112	LK32Huong Lam	1786367	755009	GL	1.61	1.17	0.13	0.1	4.01	4.04	13.71	0.189194	Interpolation
113	LK33Huong Lam	1788554	754990	GL	1.24	0.85	0.1	0.08	4.05	4.08	10.55	0.199871	Interpolation
114	LK34Huong Lam	1787117	756125	GL	1.5	1.06	0.12	0.09	4.02	4.05	10.14	0.161602	Validation
115	LK36Huong Phong	1789063	746538	GL	1.04	0.74	0.07	0.06	3.95	3.93	9.86	0.342548	Interpolation
116	LK3Hong Van	1809383	724874	GL	0.71	0.38	0.1	0.09	3.89	3.91	7.8	0.238483	Validation
117	LK41Hong Thuong	1793083	741384	GL	1.3	0.85	0.11	0.09	4.2	4.23	7.72	0.412582	Interpolation

118	LK42Nham	1797749	735994	PF	1.19	1.07	0.16	0.1	4.23	4.21	10.58	0.227687	Interpolation
119	LK45Huong Lam	1792577	753687	GL	1.08	0.55	0.08	0.05	4.11	4.14	12.28	0.171063	Interpolation
120	LK47A Dot	1780132	750492	GL	1.29	0.89	0.11	0.08	4.14	4.16	10.9	0.278134	Validation
121	LK4Hong Thuy	1809845	716367	GL	1.34	0.96	0.09	0.07	4.04	3.95	10.55	0.1853	Interpolation
122	LN10Huong Nguyen	1793739	757202	NF	1.13	0.5	0.07	0.05	4.15	4.19	11.91	0.229522	Interpolation
123	LN17Huong Nguyen	1795242	760793	NF	1.25	0.53	0.06	0.05	4.19	4.23	10.2	0.134821	Interpolation
124	LN18Huong Nguyen	1794631	762613	NF	1.29	0.56	0.07	0.06	4.18	4.22	8.02	0.388346	Interpolation
125	LN1Huong Phong	1789221	745190	NF	1.08	0.73	0.08	0.07	4.01	3.97	8	0.258233	Interpolation
126	LN21Huong Lam	1786758	751500	NF	1.25	0.9	0.1	0.08	4.08	4.04	9.58	0.324372	Interpolation
127	LN22Huong Phong	1790069	749525	NF	1.1	0.8	0.07	0.06	3.92	3.92	8.29	0.426748	Validation
128	LN26Huong Nguyen	1789457	757500	NF	1.33	0.86	0.1	0.08	4.08	4.11	11.19	0.219561	Interpolation
129	LN27Huong Nguyen	1789661	760500	NF	1.35	0.86	0.09	0.07	4.08	4.12	15.16	0.329328	Interpolation
130	LN28Huong Nguyen	1792148	760808	NF	1.29	0.63	0.08	0.06	4.13	4.18	9.78	0.344775	Interpolation
131	LN29Huong Nguyen	1789880	763500	NF	1.33	0.87	0.09	0.07	4.06	4.11	7.85	0.394751	Validation
132	LN2Hong Thuong	1789207	742805	NF	1.17	0.77	0.1	0.08	4.08	4.04	10.55	0.11618	Validation
133	LN30Huong Nguyen	1792377	763500	NF	1.32	0.64	0.08	0.06	4.13	4.18	10.55	0.386034	Validation
134	LN31Huong Nguyen	1792443	766298	NF	1.33	0.67	0.08	0.06	4.13	4.18	9.44	0.338423	Interpolation
135	LN37Huong Lam	1786520	750501	NF	1.31	0.93	0.1	0.08	4.11	4.04	9.11	0.323314	Interpolation
136	LN38Huong Lam	1789607	751137	NF	1.08	0.7	0.09	0.06	4.04	4.04	12.17	0.425403	Interpolation
137	LN39Huong Phong	1792500	751500	NF	1.03	0.51	0.08	0.05	4.08	4.12	13.2	0.309026	Interpolation
138	LN40Huong Lam	1783500	751658	NF	1.36	0.99	0.1	0.08	4.16	4.12	10.1	0.436599	Interpolation
139	LN45Huong Nguyen	1793160	759496	NF	1.26	0.6	0.08	0.06	4.13	4.18	14.19	0.381018	Interpolation
140	LN47Hong Ha	1798599	751500	NF	1.13	0.62	0.07	0.05	4.06	4.14	9.35	0.446356	Interpolation
141	LN50Hong Bac	1799489	735546	PF	1.72	1.3	0.12	0.09	4.18	4.18	9.02	0.420085	Interpolation
142	LN57Huong Phong	1795742	751974	NF	1.07	0.55	0.07	0.04	4.07	4.14	10.31	0.264193	Validation
143	LN59Hong Ha	1795500	753372	NF	1.1	0.53	0.07	0.05	4.11	4.16	12.7	0.319574	Validation
144	LN62Nham	1797564	732798	NF	1.53	1.12	0.14	0.1	4.02	4.03	10.55	0.390312	Interpolation
145	LN6Huong Nguyen	1795500	757500	NF	1.12	0.45	0.07	0.05	4.17	4.21	8.08	0.436262	Interpolation
146	LN7Huong Nguyen	1790279	757515	NF	1.27	0.78	0.09	0.07	4.08	4.11	9.93	0.407339	Interpolation
147	LN8Huong Nguyen	1795500	755156	NF	1.13	0.49	0.07	0.05	4.14	4.19	8.52	0.47552	Interpolation

148	LN9Huong Nguyen	1792962	755010	NF	1.11	0.57	0.07	0.05	4.1	4.14	9.63	0.394614	Validation
149	SX17Huong Nguyen	1803882	756611	AL	1.26	0.56	0.08	0.07	4.15	4.22	9.12	0.471819	Interpolation
150	SX20Huong Lam	1782480	751384	AL	1.16	0.8	0.1	0.09	4.18	4.16	11.84	0.351763	Interpolation
151	SX29A Ngo	1798868	738792	AL	1.54	1.14	0.1	0.09	4.37	4.45	8.69	0.424731	Interpolation
152	SX34Huong Lam	1784897	749465	AL	1.6	1.05	0.11	0.08	4.13	3.98	8.41	0.357733	Interpolation
153	SX37Hong Quang	1799459	737655	AL	1.73	1.33	0.1	0.08	4.6	4.78	8.04	0.409124	Interpolation
154	SX39Huong Lam	1783608	750028	AL	1.37	1.07	0.08	0.07	4.08	4.09	8.09	0.283967	Validation
155	SX5Huong Lam	1781132	751265	AL	1.12	0.76	0.1	0.09	4.18	4.17	10.09	0.131376	Interpolation

A2: The AHP Calculation

A2.1. Land Use Type Selection

The importance of Physical, Economic, and Social in Agricultural LUTs Selection

Criteria	Economic	Physical	Social	Weight
Economic	1.00	1.55	4.08	0.524
Physical	0.64	1.00	3.00	0.353
Social	0.25	0.33	1.00	0.123
			λ_{max}	3.002
			CI	0.001
			CR	0.002

The Matrix comparison between LUTs on Economic aspect

LUTs	Acacia	Coffee	Rubber	Banana	Vegetables	Rice	Cassava	Weight
Acacia	1.00	8.14	5.35	5.16	6.88	3.32	1.00	0.33
Coffee	0.12	1.00	0.25	0.21	0.52	0.16	0.15	0.03
Rubber	0.19	4.08	1.00	1.72	3.00	0.27	0.22	0.08
Banana	0.19	4.83	0.58	1.00	1.93	0.25	0.19	0.07
Vegetable	0.15	1.93	0.33	0.52	1.00	0.22	0.17	0.04
Rice	0.30	6.12	3.68	4.08	4.51	1.00	0.64	0.18
Cassava	1.00	6.54	4.51	5.35	5.72	1.55	1.00	0.27
							λ_{max}	7.50
							CI	0.08
							CR	0.06

The Matrix comparison between LUTs on Physical aspect

LUTs	Acacia	Coffee	Rubber	Banana	Vegetable	Rice	Cassava	Weight
Acacia	1.00	5.81	5.52	4.83	7.74	4.36	2.37	0.39
Coffee	0.17	1.00	0.34	0.34	0.37	0.21	0.22	0.04
Rubber	0.18	2.95	1.00	1.93	2.67	0.58	0.28	0.09
Banana	0.21	2.95	0.52	1.00	3.00	0.37	0.25	0.08
Vegetables	0.13	2.67	0.37	0.33	1.00	0.28	0.18	0.05
Rice	0.23	4.83	1.72	2.67	3.55	1.00	0.42	0.14
Cassava	0.42	4.58	3.55	3.94	5.62	2.41	1.00	0.23
							λ_{max}	7.55
							CI	0.09
							CR	0.07

The Matrix comparison between LUTs on Social aspect

LUTs	Acacia	Coffee	Rubber	Banana	Vegetables	Rice	Cassava	Weight
Acacia	1.00	8.56	6.88	6.88	6.54	2.67	1.55	0.36
Coffee	0.12	1.00	0.31	0.30	0.37	0.19	0.14	0.03
Rubber	0.15	3.27	1.00	1.00	1.93	0.25	0.25	0.07
Banana	0.15	3.32	1.00	1.00	1.25	0.22	0.25	0.06
Vegetables	0.15	2.67	0.52	0.80	1.00	0.18	0.16	0.05
Rice	0.37	5.35	4.08	4.51	5.52	1.00	0.80	0.20
Cassava	0.64	7.00	4.08	4.08	6.11	1.25	1.00	0.24
							λ_{max}	7.30
							CI	0.05
							CR	0.04

A2.2. Weighting of Physical, Economic, and Social Criteria for each LUT

The matrix comparison of Physical, Economic, and Social Criteria for Rice

Criteria	Physical	Economic	Social	Weight
Physical	1.00	2.33	0.67	0.36
Economic	0.43	1.00	0.43	0.18
Social	1.49	2.33	1.00	0.47
			λ_{max}	3.02
			CI	0.01
			CR	0.02

The matrix comparison of Physical, Economic, and Social Criteria for Acacia

Criteria	Physical	Economic	Social	Weight
Physical	1.00	0.37	2.26	0.26
Economic	2.69	1.00	4.52	0.62
Social	0.44	0.22	1.00	0.12
			λ_{max}	3.01
			CI	0.01
			CR	0.01

The matrix comparison of Physical, Economic, and Social Criteria for Cassava

Criteria	Physical	Economic	Social	Weight
Physical	1.00	0.88	1.00	0.32
Economic	1.14	1.00	1.32	0.38
Social	1.00	0.76	1.00	0.30
			λ_{max}	3.00
			CI	0.00
			CR	0.00

The matrix comparison of Physical, Economic, and Social Criteria for Rubber

Criteria	Physical	Economic	Social	Weight
Physical	1.00	0.49	1.22	0.25
Economic	2.05	1.00	3.71	0.58
Social	0.82	0.27	1.00	0.18
			λ_{max}	3.02
			CI	0.01
			CR	0.02

The matrix comparison of Physical, Economic, and Social Criteria for Banana

Criteria	Physical	Economic	Social	Weight
Physical	1.00	0.45	1.97	0.27
Economic	2.24	1.00	4.21	0.59
Social	0.51	0.24	1.00	0.14
			λ_{max}	3.00
			CI	0.00
			CR	0.00

A.2.3. Weighting of sub-criteria of Physical criteria for each LUT

The matrix comparison of sub-criteria in Physical criteria for rice

Sub-criteria	Soil type	Slope	Soil Texture	Precipitation	SOC	STN	Soil pH	Elevation	Soil Depth	Weight
Soil type	1.00	4.02	1.35	1.13	1.89	1.89	1.68	2.42	3.33	0.18
Slope	0.38	1.00	0.25	0.58	0.28	0.36	0.36	1.63	2.33	0.06
Soil Texture	0.74	4.02	1.00	1.24	0.94	0.97	0.88	3.09	5.54	0.15
Precipitation	0.89	1.71	0.81	1.00	1.50	1.55	2.22	2.66	2.02	0.14
SOC	0.53	3.53	1.07	0.67	1.00	2.58	2.22	4.33	4.10	0.17
Nitrogen	0.53	1.03	1.03	0.64	0.39	1.00	3.39	3.98	4.67	0.13
Soil pH	0.60	1.14	1.14	0.45	0.45	0.29	1.00	2.86	3.91	0.09
Elevation	0.41	0.61	0.32	0.38	0.23	0.25	0.35	1.00	1.50	0.04
Soil Depth	0.30	0.43	0.18	0.49	0.24	0.21	0.26	0.67	1.00	0.04

The matrix comparison of sub-criteria in Physical criteria for acacia

Sub-criteria	Soil type	Slope	Soil Texture	Precipitation	SOC	STN	Soil pH	Elevation	Soil Depth	Weight
Soil type	1.00	1.66	3.13	1.38	1.06	1.38	0.58	6.17	1.91	0.17
Slope	0.60	1.00	1.36	3.13	0.42	0.51	3.00	0.97	2.27	0.11
Soil Texture	0.32	0.73	1.00	2.84	0.60	0.51	0.72	2.76	0.19	0.08
Precipitation	0.72	0.32	0.35	1.00	0.22	0.29	0.92	0.83	0.21	0.05
SOC	0.95	2.40	1.66	4.46	1.00	0.64	2.61	3.46	2.40	0.17
Nitrogen	0.72	1.97	1.97	3.41	1.57	1.00	3.76	1.81	2.50	0.17
Soil pH	1.71	0.33	1.38	1.09	0.38	0.27	1.00	1.53	0.34	0.08
Elevation	0.16	1.03	0.36	1.20	0.29	0.55	0.55	1.00	0.88	0.06
Soil Depth	0.52	0.44	5.20	4.86	0.42	0.40	2.92	1.14	1.00	0.12

The matrix comparison of sub-criteria in Physical criteria for cassava

Sub-criteria	Soil type	Slope	Soil Texture	Precipitation	SOC	STN	Soil pH	Elevation	Soil Depth	Weight
Soil type	1.00	3.00	1.70	2.43	0.51	0.44	1.32	3.48	2.82	0.13
Slope	0.33	1.00	1.24	1.97	0.26	0.29	0.35	1.97	0.29	0.06
Soil Texture	0.59	0.81	1.00	0.92	0.29	0.27	1.73	3.48	0.45	0.07
Precipitation	0.41	0.51	1.09	1.00	0.24	0.27	0.27	0.61	2.82	0.06
SOC	1.97	3.87	3.41	4.21	1.00	1.73	2.82	4.21	4.49	0.24
Nitrogen	2.28	3.71	3.71	3.71	0.58	1.00	4.49	3.41	4.49	0.22
Soil pH	0.76	0.58	0.58	3.71	0.35	0.22	1.00	0.58	0.44	0.07
Elevation	0.29	0.51	0.29	1.63	0.24	0.29	1.73	1.00	0.58	0.05
Soil Depth	0.35	3.41	2.24	0.35	0.22	0.22	2.28	1.73	1.00	0.09

The matrix comparison of sub-criteria in Physical criteria for rubber

Sub-criteria	Soil type	Slope	Soil Texture	Precipitation	SOC	STN	Soil pH	Elevation	Soil Depth	Weight
Soil type	1.00	3.64	3.31	0.85	0.37	0.24	2.51	0.96	3.31	0.13
Slope	0.27	1.00	0.79	2.73	0.22	0.29	0.57	4.02	0.34	0.07
Soil Texture	0.30	1.26	1.00	3.23	0.30	0.39	2.54	2.02	0.27	0.08
Precipitation	1.18	0.37	0.31	1.00	0.24	0.37	1.08	0.51	0.32	0.05
SOC	2.73	4.64	3.35	4.21	1.00	2.19	4.06	4.42	3.92	0.26
Nitrogen	4.21	2.57	2.57	2.73	0.46	1.00	4.37	4.21	2.54	0.19
Soil pH	0.40	0.39	0.39	0.93	0.25	0.23	1.00	2.36	0.27	0.05
Elevation	1.04	0.25	0.50	1.97	0.23	0.24	0.42	1.00	0.29	0.05
Soil Depth	0.30	2.97	3.73	3.08	0.26	0.39	3.73	3.47	1.00	0.13

The matrix comparison of sub-criteria in Physical criteria for banana

Sub-criteria	Soil type	Slope	Soil Texture	Precipitation	SOC	STN	Soil pH	Elevation	Soil Depth	Weight
Soil type	1.00	4.79	2.28	3.41	0.29	0.33	4.40	2.59	1.29	0.14
Slope	0.21	1.00	0.58	1.73	0.26	0.34	0.51	0.86	1.24	0.05
Soil Texture	0.44	1.73	1.00	1.97	0.29	0.29	2.54	5.44	1.14	0.10
Precipitation	0.29	0.58	0.51	1.00	0.26	0.34	0.21	0.58	0.24	0.04
SOC	3.41	3.87	3.41	3.87	1.00	1.97	4.49	3.87	5.10	0.27
Nitrogen	3.00	3.41	3.41	2.94	0.51	1.00	4.79	4.79	4.49	0.22
Soil pH	0.23	0.39	0.39	4.79	0.22	0.21	1.00	0.67	0.58	0.05
Elevation	0.39	1.16	0.18	1.73	0.26	0.21	1.50	1.00	0.26	0.05
Soil Depth	0.77	0.81	0.88	4.21	0.20	0.22	1.73	3.87	1.00	0.09

A.2.4. Weighting of sub-criteria of Economic criteria for each LUT

The matrix comparison of sub-criteria in Economic criteria for rice

Sub-criteria	Labor income per day	Financial ability of the family	Accessibility of farming equipment	Ability to sell products	Weight
Labor income per day	1.00	0.68	0.42	1.21	0.18
Financial ability of the family	1.47	1.00	0.54	1.60	0.25
Accessibility of farming equipment	2.36	1.85	1.00	2.17	0.41
Ability to sell products	0.82	0.62	0.46	1.00	0.16

The matrix comparison of sub-criteria in Economic criteria for cassava

Sub-criteria	Labor income per day	Financial ability of the family	Accessibility of farming equipment	Ability to sell products	Weight
Labor income per day	1.00	1.11	1.55	2.54	0.33
Financial ability of the family	0.90	1.00	1.25	3.27	0.32
Accessibility of farming equipment	0.64	0.80	1.00	1.38	0.21
Ability to sell products	0.39	0.31	0.72	1.00	0.13

The matrix comparison of sub-criteria in Economic criteria for acacia

Sub-criteria	Labor income per day	Financial ability of the family	Accessibility of farming equipment	Ability to sell products	Weight
Labor income per day	1.00	1.57	2.96	0.42	0.24
Financial ability of the family	0.64	1.00	2.96	0.28	0.17
Accessibility of farming equipment	0.34	0.34	1.00	0.21	0.08
Ability to sell products	2.40	3.61	4.86	1.00	0.51

The matrix comparison of sub-criteria in Economic criteria for banana

Sub-criteria	Labor income per day	Financial ability of the family	Accessibility of farming equipment	Ability to sell products	Weight
Labor income per day	1.00	0.96	1.44	0.21	0.13
Financial ability of the family	1.04	1.00	2.08	0.22	0.15
Accessibility of farming equipment	0.69	0.48	1.00	0.15	0.09
Ability to sell products	4.72	4.46	6.52	1.00	0.62

The matrix comparison of sub-criteria in Economic criteria for rubber

Sub-criteria	Labor income per day	Financial ability of the family	Accessibility of farming equipment	Ability to sell products	Weight
Labor income per day	1.00	1.00	1.72	0.35	0.18
Financial ability of the family	1.00	1.00	2.54	0.34	0.20
Accessibility of farming equipment	0.58	0.39	1.00	0.23	0.10
Ability to sell products	2.86	2.97	4.32	1.00	0.51

A.2.5. Weighting of sub-criteria of Social criteria for each LUT

The matrix comparison of sub-criteria in Social criteria for rice

Sub-criteria	Labor Force Availability	Level of Information	Poverty Rate	Faming Skills	Weight
Labor Force Availability	1.00	2.59	1.63	4.58	0.45
Level of Information	0.39	1.00	0.76	2.54	0.20
Poverty Rate	0.61	1.32	1.00	1.40	0.23
Faming Skills	0.22	0.39	0.71	1.00	0.11

The matrix comparison of sub-criteria in Social criteria for cassava

	Labor Force Availability	Level of Information	Poverty Rate	Faming Skills	Weight
Labor Force Availability	1.00	2.59	0.76	2.59	0.33
Level of Information	0.39	1.00	0.45	1.97	0.17
Poverty Rate	1.32	2.24	1.00	2.94	0.38
Faming Skills	0.39	0.51	0.34	1.00	0.11

The matrix comparison of sub-criteria in Social criteria for acacia

Sub-criteria	Labor Force Availability	Level of Information	Poverty Rate	Faming Skills	Weight
Labor Force Availability	1.00	1.73	0.86	3.34	0.32
Level of Information	0.58	1.00	0.67	3.41	0.23
Poverty Rate	1.16	1.50	1.00	4.49	0.36
Faming Skills	0.30	0.29	0.22	1.00	0.08

The matrix comparison of sub-criteria in Social criteria for banana

Sub-criteria	Labor Force Availability	Level of Information	Poverty Rate	Faming Skills	Weight
Labor Force Availability	1.00	2.59	0.76	0.86	0.28
Level of Information	0.39	1.00	0.51	0.77	0.15
Poverty Rate	1.32	1.97	1.00	1.00	0.30
Faming Skills	1.16	1.29	1.00	1.00	0.27

The matrix comparison of sub-criteria in Social criteria for rubber

Sub-criteria	Labor Force Availability	Level of Information	Poverty Rate	Faming Skills	Weight
Labor Force Availability	1.00	1.00	0.47	0.83	0.18
Level of Information	1.00	1.00	0.51	0.76	0.19
Poverty Rate	2.14	1.97	1.00	2.28	0.41
Faming Skills	1.21	1.32	0.44	1.00	0.22

Academic Curriculum Vitae

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2. Employment

Lecturer	Full time	2008-current	University of Agriculture and Forestry; Hue University; Vietnam

3. Education

Ph.D. Research in Geography	Full time	2015-2019	Dept. Cartography, GIS and Remote Sensing; University of Göttingen; Germany
MSc. in Land Management	Full time	2009-2011	University of Agriculture and Forestry; Hue University; Vietnam
Engineer in Land Management	Full time	2003-2007	University of Agriculture and Forestry; Hue University; Vietnam

4. Publications

1. Tung Gia Pham*, Jan Degener, Martin Kappas (2018). *Integrated Universal Soil Loss Equation (USLE) and Geographic Information Systems (GIS) for soil erosion estimation in A Sap basin: Central Vietnam*. International Soil and Water Conservation Research, Vol 6, Issue 2, Pages 99-110. DOI: 10.1016/j.iswcr.2018.01.001
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