Combination between land suitability evaluation and multi-objective optimization mathematics model to sustainable agricultural land use planning in the coastal zone of the Mekong Delta, Viet Nam

A DOCTORATE DISSERTATION SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF ENGINEERING

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Abstract

Land evaluation is the primary content in the land-use planning process. There were many land evaluation methods which have been improved based on the FAO framework, but most of them have not been effectively assessed. The requirements of land characteristics and physical conditions supply a common view of land use types for land suitability. It is difficult in precise decision making for agricultural planning. Decision makers have to optimize productive agriculture and promote farmers' socio-economic conditions. The obstacle of the decision makers is the uncertainty because most criteria have interactive features in reality.

The simulation of land-use options is essential to support decision makers. It helps to evaluate and adjust the effects of plans because the parameters in reality are always changing. It is an excellent solution to maximize land-use efficiency. Besides, combining modelling approaches in land use planning is necessary because every approach with its single effectiveness cannot entirely assess the different parameters of sustainable land-use planning. Considering these challenges and limitations in the last studies, this dissertation aims for the development of a methodology for the monitoring and analysis of the combination between land suitability evaluation and a multi-objective optimization mathematics model to support effective land use planning towards sustainable agricultural land use planning in the coastal zone of the Mekong Delta, Vietnam.

The Mekong Delta (MD) in Vietnam has faced severe risks from the significant change of ecological systems. Especially, saltwater intrusion, sea level rise and the increasing hydroelectricity dams have sharply impacted land use. One of the significant modifications is the change from rice cultivation to shrimp cultivation where the fresh water zones are converted to brackish water zones. As an inevitable consequence, it leads to advantages and disadvantages as outcomes for the economy, society and environment which strongly affect the livelihood of farmers. So four coastal districts of Soc Trang province, the MD in Vietnam were chosen as the case study.

By comparing four evaluation methods in the crisp environment (FAO-, MCE-Method) and the fuzzy environment (methods of MAX operator and LUKASIEWICZ operator), we could find that the method of LUKASIEWICZ operator is the best method for land suitability analysis. The fuzzification via membership functions for four linguistic terms of suitability classification was used. The results reflect the mathematical cardinality of the LUKASIEWICZ operator in the fuzzy environment because this operator integrates all characteristics. Therefore, this method is useful in the land evaluation.

The LUKASIEWICZ operator in the fuzzy environment is applied in sustainable land evaluation. The objectives of the economy, society, environment and natural resources are considered for sustainable land evaluation. The LUKASIEWICZ operator coordinated the preferences of multi-objectives and continuously expressed the suitability classification in the fuzzy environment. By comparing three results of land suitability analysis: land physical suitability (by FAO method), economic suitability (by the method of LUKASIEWICZ operator) and land sustainable suitability (by the method of LUKASIEWICZ operator), we can confirm the effectiveness of sustainable land evaluation. As a necessity, it should be applied in advanced studies in sustainable land use planning. For this study area, it can be strongly recommended for agricultural land use planning during a ten year period as a master plan.

The application of FAHP (Fuzzy Analytic Hierarchy Process) for multiple criteria decision-making is based on fuzzy pair-wise comparison matrices. The result illustrates that it incorporated the preferences of nine decision makers (DMs) by weights as a compromise index. FAHP proved a useful role in multiple criteria decision-making. It is an important tool for making decision by connecting and satisfying multiple criteria of land use planning .

The FMOLP (Fuzzy Multi-Objective Linear Programming) is satisfied with the conflict of qualitative and quantitative interests of five objectives (Income, Benefit per Cost ratio, Employment, Land and Environment). We established eight scenarios to find a suitable result by the alternative priorities of five objectives. The result allocates spatial planning for 5 LUTs (Land Use Types) and handles the problem of optimization to support better agricultural land use planning. It creates a balance between the land use supply and demand for land use change. This study suggests changing land use planning by Scenario 2 (More priority for economic and environmental protection development) for the 2020-2025 period in this study area.

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List of abbreviations

AHP	Analytic Hierarchy Process
ALES	Automated Land Evaluation System
APP	Aggregate Production Planning
B/C	Benefit per Cost ratio
CEC	Cation Exchange Capacity
CI	Consistency index
CR	Consistency ratio
DMs	Decision Makers
DONRE	Department of Natural Resources and Environment
ESP	Exchange Sodium Percentage
FAHP	Fuzzy Analytic Hierarchy Process
FAO	Food Agriculture Organization
FMOLP	Fuzzy Multi-Objective Linear Programming
GDM	Group Decision Making
GIS	Geographic Information System
GIZ	Gesellschaft für Internationale Zusammenarbeit
LP	Linear Programming
LMUs	Land Mapping Units
LUP	Land Use Planning
LUTs	Land Use Types
MCDE	Multi-Criteria Decision Analysis
MCDM	Multiple Criteria Decision Making
MCE	Multi-Criteria Evaluation
MicroLEIS	Microcomputer Land Evaluation Information System
MODM	Multi-Objective Decision Making

MOFLP	Multi-Objective Fuzzy Linear Programming
MOFLPP	Multi-Objective Fuzzy Linear Programming Problem
MOP	Multi-Objective Programming
MRD	Mekong River Delta
N	None Suitable
PRA	Participatory Rural Appraisal
RI	Random Index
S1	Highly Suitable
S2	Moderately Suitable
S3	Marginally Suitable
SAR	Sodium Adsorption Ratio
SLR	Sea Level Rise
STELLA	Systems Thinking, Experimental Learning Laboratory with Animation
SWOT	Strengths, Weaknesses, Opportunities, Threats
TFNs	Triangular Fuzzy Numbers
USAID	United States Agency for International Development
USLE	The Universal Soil Loss Equation
VMD	Vietnamese Mekong Delta
VND	Viet Nam Dong
W	Weight
WLC	Weighted Linear Combination
WRB	World Reference Base

1. Introduction

1.1. Motivation of research

Land evaluation is the primary content in the land-use planning process. There are many land evaluation methods which have been improved based on the FAO framework, but most of them have not been effectively assessed. The requirements of land characteristics and physical conditions supply a common view of land use types for land suitability. As the FAO initially showed the qualitative framework for land use planning (Bagheri Bodaghabadi et al. 2015). However, the objects in planning are often unclear, it is difficult to express the level of continuity in an adaptive range in a crisp environment. For example, it is impossible to distinguish between "highly suitable" and "moderately suitable". However, there is an effective solution to dissolve the extent of its continuity in a fuzzy set (Thinh & Hedel, 2005).

Depending on the scope and objectives of the study, there are many types of land use research (Hoosbeek & Bryant, 1992). In terms of spatial scope, it can be divided into different levels (world, continent, region, province, district, commune) with plenty of map ratios. In terms of technical level, it can be studied from the planner's experience to the detailed calculation of qualitative and quantitative criteria. Besides, depending on natural conditions, social practices and political mechanisms lead to differences in land use planning (Mccall, 2003).

Spatial planners must consider a large number of criteria, objectives and human preferences (Thinh & Hedel, 2005). The simulation of different land-use options is essential to support the decision maker. It helps to evaluate and adjust the effect of plans because the parameters in reality are always changing. It is an excellent solution to maximize land-use efficiency (Chang & Ko, 2014). Because of the fast development of technology, geographic information systems have become a useful tool in cultivation. Especially, with Global Navigation Satellite Systems (GNSS), farmers can make changes to crops on their farm to adapt to the dynamics of soil, vegetation, topography (Bill et al. 2011).

In the context of rapid changes in natural conditions due to climate change impacts and economic efficiency requirements, land use planning needs to consider many objectives. According to previous research methods, most of them are based on trade-offs as a balance between different multi-objective programming (MOP) of the stakeholders' participation in order to achieve an agreement in the process of making the final decision for land use planning (Chang et al. 1995; Seppelt & Voinov, 2003). It is difficult in decision making for precise agricultural planning. Decision makers have to optimize productive agriculture and to promote farmers' socio-economic conditions. In recent decades, fuzzy mathematical programming has been applied as the most appropriate approach to handle agricultural land-use planning (Amini, 2015).

Wassmann et al. (2004) used a hydrology model to estimate changes in water levels in VMD under two sea level rise (SLR) scenarios of 20 cm and 45 cm. They predicted that the average increment in water levels in VMD is about 14.1 cm and 32.2 cm, respectively, and that about 0.6 million ha to 2.3 million ha among 4 million ha of the VMD will be flooded due to the SLR. Previous impact assessments on the effect of SLR in the VMD also showed that about 1.5-2.0 million ha in the VMD would be at higher risk of tidal threat. More recently, Khang et al. (2008) used a simulation model to predict the consequences of two medium-term (the mid-2030s) and long-term (mid-2090s) scenarios. Their predictions can be summarized as follows: - Sea level rise will be about 20 cm in the mid-2030s and 45 cm in mid-2090s

- Salinity intrusion will go up inland (upstream) by 10 km in the mid-2030s and 20 km in mid-2090s, or up to 20 km (mid-2030s) and 35 km (mid-2090s) in the paddy field.
- Triple rice cropping will be reduced by 1.8% during the mid-2030s, and in mid-2090s double rice cropping will be reduced by 2.7% and triple rice cropping will be reduced by 1.8%.

Coastal areas of the Mekong Delta in Vietnam are increasingly experiencing salinity intrusion in freshwater systems, in part due to climate change induced sea level rise, compromising agricultural production and domestic water supply (Renaud et al. 2015). Salinity intrusion seriously affects agricultural activities, particularly rice production (Kotera et al. 2008; Chen et al. 2012).The Mekong River Delta has 13 provinces with 4,057,060 hectares, of which 2,607,100 ha (64.2 %) are agricultural area, where the production of agriculture characterizes the economy, where rice production dominates, and its area is growing very fast (General Statistics Office, 2014). The agro-ecological zones of the MRD can be characterised by a combination of distinct soil types and hydrological features. About 25% of the soils of the MRD can be classified as alluvial with relatively high soil fertility; the remaining soils are either acid sulfate soils or salt soils. Although acid sulfate soils can be found in different sections of the MRD, salt soils are confined to the coastal areas and result from reoccurring salinity intrusion in the dry season. The upper end of the Delta comprises flood-prone areas that could be either alluvial or acid sulfate soil (Phong et al. 2016). In recent years, the change in land use has strongly affected the properties and qualities of major soil groups. The conversion of the legend of the soil map classified by the 1998 WRB system into the soil map classified by the 2006 system has been completed. According to the conversion result, there are ten major soil groups: Albeluvisols, Alisols, Arenosols, Fluvisols, Gleysols, Histosols, Leptosols, Luvisols, Plinthosols and Solonchaks with 60 soil types found and named based on the WRB 2006 system. Those soil types and the map can be used for land suitability assessment and land use planning, which can be used for the conservation of agricultural economic conversion for the Mekong Delta in the sustainability projection (Minh et al. 2016).

Land use planning (LUP) in the coastal zone of the Mekong Delta, Viet Nam is challenged by strongly contrasting and quickly shifting land use systems. In addition to that, the planning procedures applied in Vietnam are viewed by many stakeholders as top-implementation. Therefore, it is essential to have a land use planning approach that can overcome these problems (Trung, 2006). The Mekong Delta (MD) is being deeply affected by climate change. Accordingly, the issues of drought and saltwater intrusion have had a significant influence on people’s lives and farming activities in the region, and have become the concern of many levels of authorities. By February 2016, saltwater has been present on 40% of farmland in the MRD (Can Tho University, 2016). The areas have been affected with a salinity of over 24 g/l clearly increasing, and the length of salinity intrusion in the Vam Co River has reached 93 km. (Southern Institute of Water Resources Research, 2016). Drought and salinisation are increasingly common in the Central Coast and the Mekong Delta. Some land areas are no longer suitable for rice cultivation. Vietnam is thus forced to switch to other crops or aquaculture. The National Assembly has approved the resolution on revising the land use master plan until 2020 and the national land use plan for 2016-2020; around 400 thousand ha of rice cultivation land will be set aside for other uses amid frequent drought and salinity. According to Vietnam's climate change scenario, by 2020, sea level is expected to rise by 12cm, affecting 6 thousand ha of rice cultivation land, including 4 thousand ha in the Mekong Delta. Rice crops are profoundly affected by hydroelectric dams upstream (National Assembly Standing Committee, 2016).

Land use changes in the coastal areas in Soc Trang province have happened due to the physical settings and led to improvements of the financial income of the local farmers. The land use has changed strongly from 2000 to 2008. The area used for rice has significantly decreased whereas the area of intensive shrimp farming has increased (Tri et al. 2008). The Intergovernmental Panel on Climate Change (IPCC) commissioned a Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). This report further recognizes that sea level rise (SLR) drove salinity intrusion in coastal areas, which is a global problem (Werner et al. 2013). In particular, cropping patterns have changed from double rice to shrimp-rice; extensive shrimp and intensive shrimp systems, and so forth. In the four coastal districts of Soc Trang province, the sodification process in the soil will be continued from 2000 to 2010 with high ESP (Exchange Sodium Percentage) values up to 85% in extensive and intensive shrimp crops in the year 2015. Shrimp and Rice Shrimp alternative cropping gave a high benefit for farmers. However, the risks of Shrimp and Rice Shrimp alternative cropping were also rather more than in another type of crops. There was 20-30% failure annually for farmers; it made an unsustainable livelihood. The main problems are changes in soil and water qualities (Kiet, 2008).

During the planning, because of ambiguous or uncertain information caused by the vagueness of decision makers' subjective preference or the uncertainty of objective information, the conventional multi-objective linear programming (MOLP) model is not suitable for such decision-making in such a fuzzy environment (Zeng et al. 2010). The decision makers are facing the multi-objective optimisation problem in the allocation of land-use planning – economic efficiency, employment, and the environment – in agricultural land-use planning. Using the model in the planning of agriculture land use will save time, enable quick responses to requests to provide prompt information, reduce cost and improve labor productivity. Therefore, the development targets and availability of resources were translated into mathematical formulas and solved by multiple linear programming software. By gradually imposing constraints and goal restrictions, the land use planner and policy maker can recognise which input to invest and if their goals are feasible. In reality, decision-making problems are very vague and uncertain in many ways. Most of the criteria have interdependent and interactive features, so they cannot be evaluated by conventional measuring methods (Chen et al. 2011). Therefore, a study of the integration of land suitability evaluation and Fuzzy multi-objective linear programming (FMOLP) is built to solve multi-objective optimisation in the allocation of agricultural land-use. A case study in Soc Trang province is necessary and allows improvements in strategic land-use planning.

1.2. Research questions and objectives

1.2.1. Research questions

The research attempts to answer the following questions:

- Question 1: Which method can be applied for land suitability analysis in the crisp and fuzzy environment?
- Question 2: How to determine the problems of agricultural land use planning under conditions of uncertainty by multiple objectives?
- Question 3: How the result of land suitability evaluation should be integrated into a multi-objective optimization model of the allocation of agricultural land-use?
- Question 4: How to satisfy the requirements for decision makers in sustainable agricultural land use planning?

1.2.2. Research objectives

This study aims to process and provide information to support sustainable agricultural land use planning for decision makers. The research proposal study constructed multi-objective optimization mathematics model that integrate planning for sustainable management of land resources with land suitability evaluation, which searches for optimal solutions to a land use allocation with multiple objectives and constraints. The study will be addressed in the following objectives:

1. to compare the crisp environment with the fuzzy environment and to find a more suitable method for land suitability analysis,

2. to develop indicators for the economy, society, natural resources and environment for fuzzy land suitability analysis,

3. to apply Fuzzy Multi-objective Linear Programming (FMOLP) in the allocation of agricultural land-use, and

4. to incorporate the preferences of decision makers using a compromise index into land suitability analysis.

1.3. Organization of the dissertation

This dissertation consists of six chapters. After the introduction provided in this chapter, theoretical background for this study is introduced in chapter 2. First, it provides the conceptual basis in the context of land suitability analysis, land use planning and fuzzy set theory and fuzzy multi-objective linear programming. Following, the theory and history of related approaches and their strengths and limitations are introduced. This chapter is essential to provide definitions, theoretical background and the last studies with methodologies and results.

Chapter 3 is concerned with the study area of four coastal districts in Soc Trang province, Vietnam. It describes physical, economic, and social conditions leading to land use changes. After that agricultural land use planning of this study area is introduced in the provincial context of Soc Trang province. Also, the spatial and non- spatial database for this study is described.

Chapter 4 describes the methods used in this study. It consists of three parts. In the first part, data collection methods are introduced. The second part presents land physical evaluation methods, which includes the FAO and MCE methods in the crisp environment and the MAX and LUKASIEWICZ in the fuzzy environment. Furthermore, the operator LUKASIEWICZ in the fuzzy environment is identified to apply in land economic and sustainable suitability. The third part gives information about Fuzzy Multi-objective linear programming (FMOLP). The variables are identified for establishing five objective functions to optimize economic, social, and environmental effects. Besides the constraint conditions of land suitability area, agricultural land area, agricultural labor force and cost are established. The single objective linear programming is solved as a basis to establish fuzzy linear membership functions of five objectives; then they were interacted by the fuzzy satisfying method. The incorporation of preferences of decision makers using a compromise index to identify weights by Fuzzy analytic hierarchy process- Group decision making (FAHP- GDM) is based on the crisp and fuzzy pair-wise matrix from nine experts. Eight scenarios are designed to present different land use planning trends.

Chapter 5 presents and discusses the findings generated by the methods in chapter 4.

Chapter 6, finally, answers the research questions proposed in chapter 1 and major findings are provided. Based on the study findings, the development recommendations and the future work are also presented.

2. Overview of land suitability analysis, land use planning and multi criteria decision analysis

This chapter shows a brief outline of the fundamental theoretical principles of this study. The main contents are related to researches on sustainable agricultural land-use planning. They are introduced and compared to give an impressive overview of the advantages and disadvantages of these researches.

2.1. Land suitability analysis

Land evaluation is suggested to measure the suitability of land for particular uses in agriculture. Land evaluation can be determined by biophysical parameters and socioeconomic conditions of an area (FAO, 1976). In other words, land evaluation is defined as the process of estimating the possible behaviour of the land when utilized for a particular purpose; this use could be the current one or a potential one. In this sense, land evaluation could be regarded as a tool to make decisions about the land (FAO, 1976). Bio-physical factors tend to remain stable, unlike socioeconomic factors that are affected by social, economic, and political settings (Dent & Young, 1981; Triantafilis et al. 2001). The information about the physical condition is an essential factor to identify opportunities for optimal land use (FAO, 1983). Land suitability evaluation makes the sustainable use of the land feasible (Vargahan, 2011). Land evaluation for sustainable land-use management has to take into account several different issues - such as natural, environmental and socioeconomic conditions – and thus, it is multi-criteria decision analysis (Dinh & Duc, 2012).

Qualitative land suitability evaluation is based on the physical parameters affecting the yield of agricultural crops and the socio-economic factors are not considered in such evaluation (FAO, 1983). In quantitative land suitability evaluation, economic aspects of land evaluation, such as the influence of environmental, physical factors on crop production and the total of yield per unit are considered (Rossiter, 1995).

Different methodologies have been developed for land suitability evaluation. Several of these methods were developed before the FAO Framework for Land

Evaluation. The FAO framework for land evaluation is considered as a set of methodological guidelines rather than a land classification system. It was mainly designed to fit any environment and at any scale, and to be utilized primarily in regions with restricted basic data (FAO, 1976).

Since the FAO framework for land evaluation was published, some computer systems have been used to develop land evaluation methods. ALES: a framework for land evaluation using a microcomputer (Rossiter, 1990). Land evaluation and conservation of semiarid agrosystems in Zaragoza using an expert evaluation system and IDRISI (Machin & Navas, 1995). A land evaluation decision support system (Micro LEIS DSS) for agricultural soil protection with special reference to the Mediterranean region (Mayol et al. 2004).

The Geographic Information System (GIS) technique was integrated into the land suitability analysis. In farming systems, the fuzzy set model, AHP method, and GIS technique were integrated to create land suitability map for tobacco production in Shandong province of China. The modelling results are based on individual land mapping unit, which facilities the land resource allocation. It provides a useful approach to increase land use efficiency for tobacco production (Zhang et al. 2015). Land suitability using a GIS-based model was established a spatial model for land suitability assessment for wheat crop in Egypt. The model allows obtaining results that corresponded with the current conditions in the area ((Baroudy, 2016). Land suitability analysis is one of the most beneficial applications of the GIS in planning and managing land recourses. It developed a fuzzy multi-criteria decision making technique integrated with the GIS to assess suitable areas for rice cultivation in Amol District, Iran. The results indicated that an efficient strategy to increase the accuracy of the weight of the criteria affecting the analysis of land suitability (Maddahi et al. 2017). The integration of GIS, Fuzzy sets and AHP methods has been successfully in land suitability analysis for soybean crops in Kebumen District, Indonesia. This integration was a powerful combination of techniques to be strongly recommended replacing conventional land suitability analysis methods and can be used as a basis for agricultural planning to optimize soybean production (Subiyanto et al. 2018). In urban planning, land suitability analysis using AHP model is the primary tool in urban planning and decision-making process. It offered information on the existing urban land use pattern and established urban amenities in future (Parry et al. 2018).

2.2. Land use planning

Land use planning is an evaluation process of land characteristics and water supply ability, Land-use will be identified due to economic and social conditions. It has to adapt to human needs but to protect natural resources for the future. The major objective of land use planning is the change which leads to better management (FAO, 1993).

Land use planning is a systematic and iterative procedure carried out in order to create an enabling environment for sustainable development of land resources which meets people's needs and demands. It assesses the physical, socio-economic, institutional and legal potentials and constraints with respect to optimal and sustainable use of land resources, and empowers people to make decisions about how to allocate those resources" (FAO and UNEP, 1999)

It is increasing the competition between land-use and other purposes. So land use planning is a great solution to balance this conflict. Since the 1990s, land use planning is an essential topic in the context of German development cooperation in rural development. On behalf of the Federal Ministry for Economic Cooperation and Development (BMZ), the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH has contributed significantly to the exchange of knowledge and the development of concepts and tools. Experiences of a high number of partner countries have been evaluated systematically and integrated into the concept development resulting in the land use planning guiding principles published in 1995. Land use planning was understood and still is as a social process that aims at a sustainable land use and balance of interests in rural areas (GIZ, 2012).

National level: At the national level, planning is concerned with national goals and the allocation of resources. In many cases, national land-use planning does not involve the actual allocation of land for different uses, but the establishment of priorities for district-level projects. A national land-use plan may cover:

• Land-use policy: balancing the competing demands for land among different sectors of the economy food production, export crops, tourism, wildlife conservation, housing and public amenities, roads, industry;

• National development plans and budget: project identification and the allocation of resources for development;

• Coordination of sectoral agencies involved in land use;

• Legislation on such subjects as land tenure, forest clearance and water rights.

National goals are complex while policy decisions, legislation and fiscal measures affect many people and wide areas. Decision-makers cannot possibly be specialists in all facets of land use, so the planners' responsibility is to present the relevant information in terms that the decision-makers can both comprehend and act on.

District level: District level refers not necessarily to administrative districts but also to land areas that fall between national and local levels. Development projects are often at this level, where planning first comes to grips with the diversity of the land and its suitability to meet project goals. When planning is initiated nationally, national priorities have to be translated into local plans. Conflicts between national and local interests will have to be resolved. The kinds of issues tackled at this stage include:

• The sitting of developments such as new settlements, forest plantations and irrigation schemes;

• The need for improved infrastructure such as water supply, roads and marketing facilities;

• The development of management guidelines for improved kinds of land use on each type of land.

Local level: The local planning unit may be the village, a group of villages or a small water catchment. At this level, it is easiest to fit the plan to the people, making use of local people's knowledge and contributions. Where planning is initiated at the district level, the programme of work to implement changes in land use or management has to be carried out locally. Alternatively, this may be the first level of planning, with its priorities drawn up by the local people. Local-level planning is about getting things done on particular areas of land - what shall be done where and when, and who will be responsible (FAO, 1993).

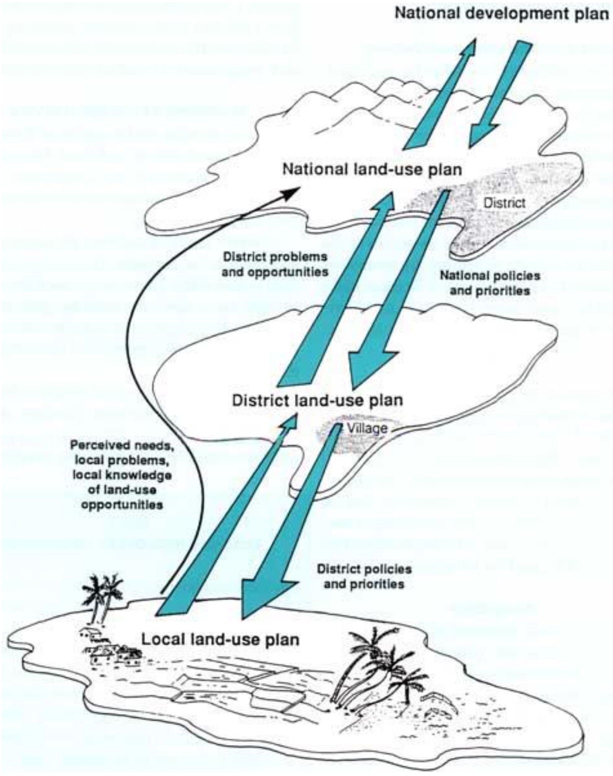


Figure 2.1. Two-way links between planning at different levels

Source: (FAO, 1993)

Principles of the formulation of master plans and plans on land use in Vietnam:

• To conform to strategies, master plans and plans on socio-economic development, national defense and security.

• To formulate from the master level to detailed level; the master plan on land use of the subordinate level must conform to the master plan on land use of the superior level; and the land use plans must conform to the master plan on land use approved by competent state agencies. The national master plan on land use must take into account specific characteristics and linkages of the socio-economic regions; and the district-level master plan on land use must demonstrate the contents of the commune-level land use.

• To use land economically and efficiently.

- Reasonable exploitation of natural resources and environmental protection; climate change adaptation.
- To protect and embellish cultural-historical relics and scenic spots.
- To be democratic and public.
- To ensure priority for using the land fund for the purposes of national defense and security, serve national and public interests, food security and environmental protection.
- Master plans and plans of the sectors, fields and localities that use land must conform to the master plans, plans on land use already decided or approved by competent state agencies.

The system of master plans and plans on land use: National master plans and plans on land use, Provincial-level master plans, plans on land use; District-level master plans, plans on land use; Master plans, plans on land use for national defense; Master plans, plans on land use for security. Periods of master plans and plans on land use are 10 years.

A district-level master plan on land use must be formulated based on:

- The provincial-level master plan on land use;
- The master plans for the socio-economic development of the province and district;
- Natural and socio-economic conditions of the district, town or provincial city;
- The current land use status, land potential and results of implementation of the district-level master plan on land use in the previous period;
- Land use demands of all sectors and fields, the district and communes;
- Land use quotas;
- Scientific and technological advances involving land use.

A district-level master plan on land use has the following contents:

- Orientation for land use in 10 years;

- Determination of the areas of the land types already allocated in the provincial-level master plan on land use and the areas of land types in accordance with land use demands of the district and communes;
- Determination of land use zones by land use function for each commune-level administrative unit;
- Determination of the areas of land types for each commune-level administrative unit;
- The district-level land use planning map in which the zones already planned for paddy land and changes of land use purposes must be demonstrated in detail for each commune-level administrative unit;
- Solutions for the implementation of the master plan on land use.

Adjustment of a master plan on land use is only conducted in the following cases:

- There are adjustments to the strategies for socio-economic development, national defense, and security or master plan for the development of socio-economic regions and such adjustments result in a change of the land use structure;
- Natural disasters or wars result in changes in the land use purposes, structure, locations and area;
- There are adjustments in the master plan on land use of the immediate superior level which affect the master plan on land use of the concerned level;
- There are adjustments to local administrative boundaries.

Adjustments to a land use plan are only conducted when there are adjustments in the master plan on land use or there are changes in the ability to implement the land use plan (The National Assembly Viet Nam, 2013).

Figure 2.2 presents the relationship between land use planning and agricultural land use planning: Agricultural land use planning is one of the basis quotas for land use planning. Land use planning is based on the planning and forecasting requirements of agricultural sectors, but it is macroscopic characteristic, to control and reconcile agricultural land use planning. These two types of planning have interrelated relationships that are extremely necessary and irreplaceable (The National Assembly Viet Nam, 2013).

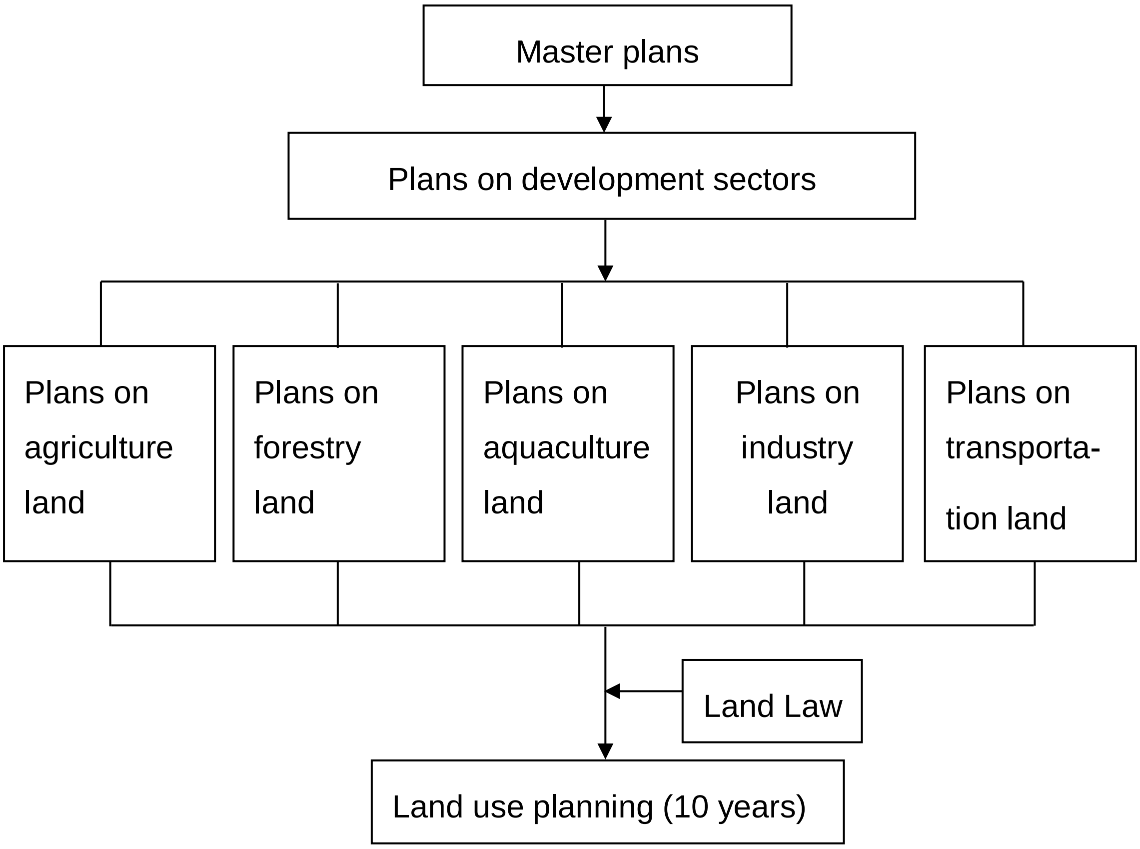


Figure 2.2. The relationship of plans on land use in Vietnam

2.3. Mathematical models in spatial planning

2.3.1. Analytic Hierarchy Process

A paper surveys the GIS-based multi criteria decision analysis (GIS-MCDA) approaches using a literature review and classification of articles from 1990 to 2004. An electronic search indicated that over 300 articles appeared in refereed journals. The paper provides taxonomy of those articles and identifies trends and developments in GIS-MCDA (Malczewski, 2006). Spatial planning involves decision-making techniques that are associated with techniques such as Multi Decision Criteria Analytic (MCDA) and Multi Criteria Evaluation (MCE). Combining GIS with MCDA methods creates a powerful tool for spatial planning (Jankowski, 1995). The integration of GIS and multi criteria decision analysis has attracted significant interest over the last 15 years or so (Malczewski, 2006).

There has been a growing interest and activity in the area of multiple criteria decision making (MCDM), especially in the last 20 years. Modelling and optimization methods have been developed in both crisp and fuzzy environments (Carlsson & Fullér, 1995).

The Analytic Hierarchy Process (AHP) method was developed by (Saaty, 1977). It is an extension to Weighted Linear Combination (WLC). AHP is a procedure that seeks to consider the context of the spatial planning decision, identifying and arranging the criteria into different groups (Vogel, 2008; Abdi et al. 2009). AHP is based on three principles: decomposition, comparative judgment, and synthesis of priorities (Eldrandaly et al. 2005). AHP has been applied in many economic, social, political and technological areas. It supports decision making, planning, conflict resolution and forecasting, rounds out the diversity of application areas of the AHP. The AHP offers economists a substantially different approach to deal with economic problems through ratio scales. The main mathematical models on which economics has based its quantitative thinking up to now are utility theory which uses interval scales and linear programming (Saaty & Vargas, 2012).

AHP involves three stages of problem solving: the principles of decomposition, comparative judgments, and synthesis of priority (Sari et al. 2008).

Stage 1: Develop the analytic hierarchy process procedure:

At this stage, the most and least important elements of the decision problem should be defined and entered into the AHP procedure. At the top level of the hierarchy, the main goal of this decision problem should be defined, and below that, the hierarchy descends from the general to the more specific until a level of attributes is reached. Each level must link to the next-highest level in the hierarchy. In general, the hierarchy involves four levels: goal, objectives, attributes and alternatives. These alternatives can be represented in a geographic information system database. Map layers comprise the element values assigned to alternatives, and then alternatives are linked to the higher- level attributes.

Stage 2: Perform a pair-wise comparison of decision elements:

The matrix pair-wise comparison is considered the fundamental input for the AHP method. The pair-wise comparisons matrix was developed in the context of the AHP procedure. It is based on forming judgments between two particular criteria rather than attempting to prioritize an entire list of parameters by Saaty (2008), and is designed to determine the weights of criteria for the parameters of a composite suitability map layers. It includes three main steps (Lai, 1995).

- The first stage is developing the pair-wise comparison matrix by using scale ranges from 1 to 9: equal importance, equal to moderate importance, moderate importance, and moderate to strong importance, strong importance, strong to very strong importance, very strong importance, very to the extremely strong importance and extreme importance. This scale was designed by Saaty to define how important A is relative to B.
- The second stage includes three main operations: (1) add the values in columns of the PCs matrix; (2) divide each element in the PCs matrix by its column total; and (3) calculate the average of the elements in each row of the standardized matrix: i.e., divide the sum of standardized scores for each row by the number of variables (Lai, 1995).
- The final stage includes the determination of the Consistency Ratio (CR) of the pair-wise comparison matrix. The CR is a measure of how much difference is acceptable and it must be less than or equal to 0.1. If the Consistency Ratio is greater than 10 %, the pair-wise comparisons matrix should be recalculated.

The calculation of the consistency index (CI) is based on the observation that λ is always larger than or equivalent to the number of criteria or parameters (n) under consideration for positive, reciprocal matrixes. Consequently, $\lambda - n$ is considered as a measure of the degree of inconsistency. This measure can be standardized as follows:

$$CI = (\lambda - n) / (n - 1) \tag{2.1}$$

Where CI refers to the consistency index; this gives measures of departure from consistency. Also, the consistency ratio (CR) can be computed from the pair-wise comparison matrix as follows:

$$CR = CI / RI \qquad (2.2)$$

Where RI is the random index; this gives the consistency index of a randomly created pairwise comparison matrix (Malczewski, 1999).

Stage 3: Construct an overall priority rating:

At this stage, the composite weights are created. The composite weights are derived by multiplying the relative weights matrix at each level of the hierarchy. The composite weights show the rating of alternatives with respect to the overall goal and also represent scores of decision alternatives (Saaty, 2008). The overall score of the alternative can be computed by using equation 4.9 described in the section on the weighted linear combination.

The main advantage derived from the application of the AHP method to the model of land suitability analysis is that the AHP allows the decision-makers to know the relationship between the goals, criteria, sub-objectives and alternatives. The disadvantage of the use of the AHP is that the scale range 1 to 9 is considered an unbalanced scale because the parameters in the AHP can be organized at the same level. The difficulty in using the AHP method is to compare attributes. For too many criteria the pair-wise comparisons analysis must be run a number of times (Malczewski, 1999; Prakash, 2003).

It makes a decision in an organized way, to generate priorities we need to decompose the decision into the following steps (Saaty, 2008) :

1. Define the problem and determine the kind of knowledge sought;

2. Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives);

3. Construct a set of pair-wise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it;

4. Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below.

Do this for every element. Then for each element in the level below, add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives at the bottom most level are obtained.

2.3.2. Fuzzy set theory

Fuzzy set theory was introduced by Zadeh (1965) although the underlying concepts predate this. Overviews have been provided by (Zimmermann, 1978), (Jager, 1995) and (Pedrycz & Gomide, 1998). In the real world, the decision-making problems are very unclear and uncertain in a number of ways. Most of the criteria have interdependent and interactive features, so they cannot be evaluated by conventional measuring methods (Chen et al. 2011).

A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function, which assigns to each object a grade of membership ranging between zero and one. The notions of inclusion, union, intersection, complement, relation, convexity, etc., are extended to such sets, and various properties of these notions in the context of fuzzy sets are established. In particular, a separation theorem for convex fuzzy sets is proved without requiring that the fuzzy sets be disjoint (Klir & Yuan, 1995).

According (McBratney & Odeh, 1997), the fuzzy set can be mathematically defined as follows:

$$\mathrm{A} = \{x, \mu_A(x)\} \text{ for each } x \in \mathrm{X} \tag{2.3}$$

Where μ_A is the membership function that defines the grade of the membership function of x in A. The membership function μA(x) takes values between 1 and 0 inclusive for all A. If X = $\{x_1, x_2, x_3, \ldots, x_n\}$, the previous equation can be written as follows:

$$\mathrm{A} = \{x_1, \mu_A(x_1)\} \cup \{x_2, \mu_A(x_2)\} \cup \{x_3, \mu_A(x_3)\} \cup \ldots \cup \{x_n, \mu_A(x_n)\} \tag{2.4}$$

In plain words equations 2.3 and 2.4 mean that for every x belongs to the set X, there is a membership function μ_A that describes the degree of ownership of x in A.

The fuzzy membership function as $M_{A(x)} \rightarrow [0,1]$ with each element x belonging to X with a grade of membership $\mu_{A(x)} \in [0,1]$. In this way $\mu_{A(x)} = 0$ represents that the value of x does not belong to A and $\mu_{A(x)} = 1$ means that the value belongs completely to A. On the other hand, $0 < \mu_{A(x)} < 1$ means x belongs in a definite degree to A.

2.3.3. Fuzzy membership functions

Fuzzy Sets are classes without sharp boundaries; that is, the transition between membership and non-membership of a location in the class is gradual (Zadeh, 1965). A fuzzy set is described by fuzzy membership functions that range from 0.0 to 1.0, representing a continuous increase from non-membership to complete membership. Examples of fuzzy set membership functions are given in Figures 2.3, 2.4 and 2.5.

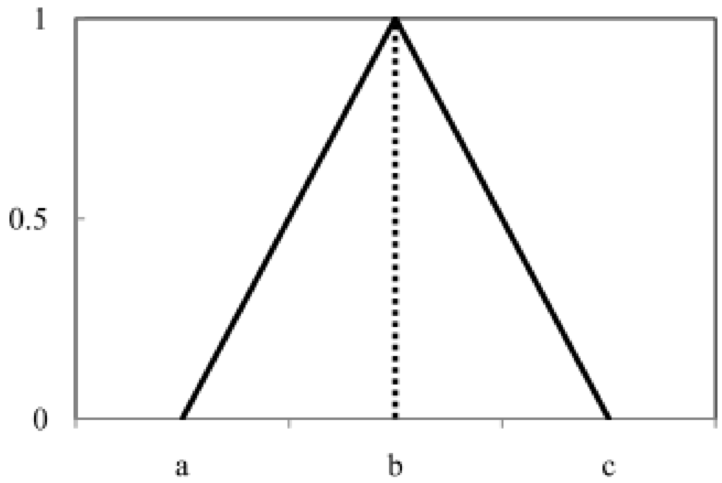


Figure 2.3. Triangular fuzzy membership function

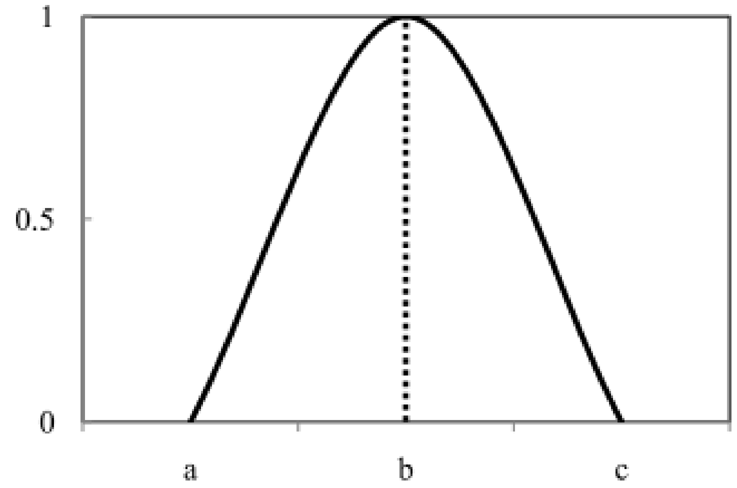


Figure 2.4. Gaussian fuzzy membership function

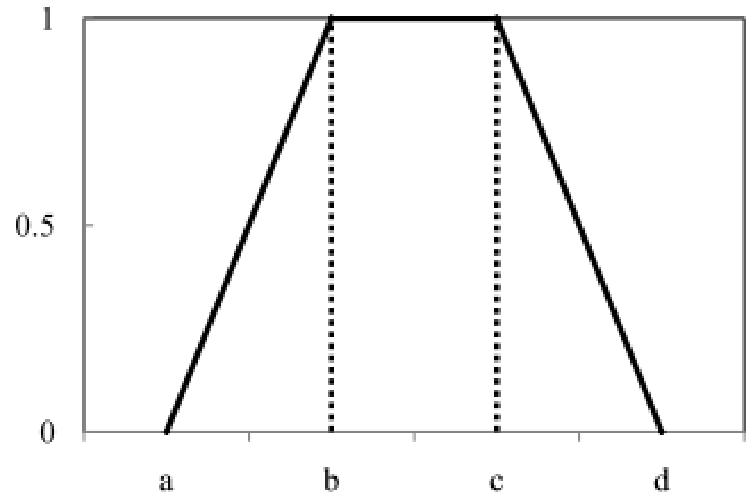


Figure 2.5. Trapezoid- shaped fuzzy membership function

2.3.4. Fuzzy logic operations

The primary operations that can be performed utilizing fuzzy sets are a generalization of those that can take place with crisp sets (Zadeh, 1965). For defining these operations, McBratney & Odeh (1997) assumed two fuzzy sets, A and B, each of which belongs to finite sets X of real numbers.

Minimum and maximum operators are used commonly in fuzzy systems because they realized conjunction and disjunction over fuzzy sets. Besides, they are easy to implement and supply good results when fuzzy system is tuned (Zavala et al. 2009).

There are two fuzzy sets A and B, they belong to a set X of real numbers X. The intersection of A ∩ B contains both A and B by the membership function:

$$\mu_{A\cup B}(x) = \min\ (\mu_A(x), \mu_B(x)) \quad (2.5)$$

$\text{Min}(\mu_A(x), \mu_B(x))$ is the minimum of the membership degrees of element x in the two sets A and B. The fuzzy intersection by min operator is the logical AND in the Boolean (Figure 2.6).

The union of A U B contains all elements of A and B by the membership function:

$$\mu_{A\cup B}(x) = \max\ (\mu_A(x), \mu_B(x)) \quad (2.6)$$

$\text{Max}(\mu_A(x), \mu_B(x))$ is the maximum of the membership functions of element x in the two sets A and B. The fuzzy intersection by min operator is the logical OR in the Boolean (Figure 2.7). It is used to combine and aggregate the output sets of the rules by fuzzy union.

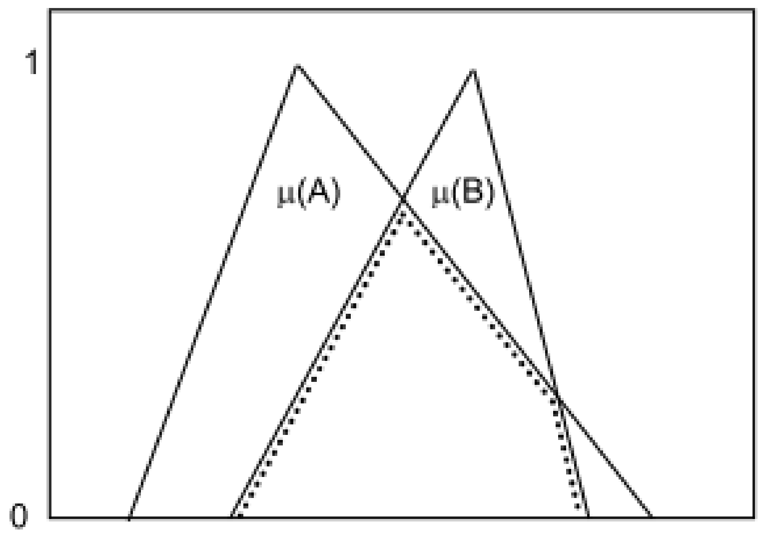


Figure 2.6. Fuzzy intersection of fuzzy sets A and B.

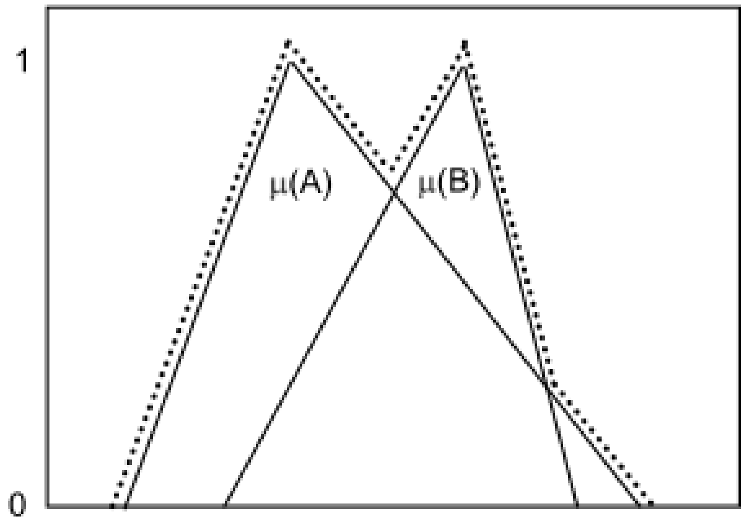


Figure 2.7. Fuzzy union of fuzzy Sets A and B.

Various kinds of FMOLP models have been proposed to deal with different decision-making situations that involve fuzzy values in objective function parameters, constraints parameters, or goals. Transforming a FMOLP problem into a crisp programming one is still employed by researchers (Lai & Hwang, 1994).

For maximizing solution efficiency, there are two kinds of operators: the min-operator and the product operator. The maximizing solution always turns out to be an efficient solution, for the min-operator as well as for the product operator (Zimmermann, 1985). The min-operator is achieved to aggregate fuzzy sets (Liang, 2009), and is used to model the intersection of the fuzzy sets of objectives and constraints (Kahraman, Ulukan, & Tolga, 1994). However, the min-operator is not always suitable to represent fuzzy preferences for DMs. Especially, DMs do not always apply the min-operator in general decision situations to combine fuzzy goals (Sakawa & Kato, 2009).

The FMOLP approach is easy to solve computationally and is not so demanding with respect to information required from the DM in each interaction. The aim is to provide the DM with a flexible decision tool which can be changed according to the different solutions automatically and is easily incorporated in the model (Borges & Antunes, 2002). It is applied in many fields of life such as optimizing the use of natural resources, achieving the highest economic efficiency but at the same time reducing investment costs. Liang (2006) solves the interactive fuzzy multi-objective transportation problem with a piecewise linear membership function. It accomplishes to simultaneously minimize the total distribution costs and the total delivery time with reference to fuzzy available supply and total budget at each source, and fuzzy forecast demand and maximum warehouse space at each destination. Zeng et al. (2010) applied FMOLP with triangular fuzzy numbers to optimize cropping patterns under different water-saving levels and satisfaction grades for water resources availability.

The interactive FMOLP method includes the following steps (Liang, 2006):

1. Formulate the original fuzzy MOLP model for the considered problem.

2. Given the minimum acceptable membership level, α, and then convert the fuzzy inequality constraints with fuzzy available resources (the right-hand side) into crisp ones using the weighted average method.

3. Specify the degree of membership for several values of each objective function.

4. Draw the piece-wise linear membership functions for each objective function.

5. Formulate the piece-wise linear equations for each membership function.

6. Introduce an auxiliary variable, thus enabling the original fuzzy multi-objective problem to be aggregated into an equivalent ordinary LP form using the minimum operator.

7. Solve the ordinary LP problem, and execute the interactive decision process. If the decision maker is dissatisfied with the initial solutions, the model must be adjusted until a set of satisfactory solutions is derived.

There were some studies to solve nonlinear and linear programming problems in many fields. Tanaka & Asai, (1984) applied max and min operator with triangular fuzzy numbers to formulate FMOLP. In the study of Lai & Hwang (1992), in order to maximize the capacity of achieving higher profit, they used triangular fuzzy numbers to maximize the best possible value, minimizing the risk of lower profit. Turtle et al. (1994) showed the application of fuzzy sets in linear programming to manage the problems of water quality under uncertainty information. Torbert et al. (2008) used fuzzy modelling theory in soil quality assessment. The content of the study defined two general types of fuzzy soil quality indicators. This approach supported effectively a better understanding of soil quality. In the crop area planning, Zeng et al. (2010) proposed a FMOLP model with triangular fuzzy numbers. The results showed the optimal cropping patterns under different water-saving levels of water resources availability. It also combined the satisfaction of decision makers and suggests alternative scenarios for better decision making.

Shaw et al. (2012) present an integrated approach applying a fuzzy analytic hierarchy process and fuzzy multi-objective linear programming for selecting the appropriate supplier in the supply chain. This approach handles the realistic situation when there is information vagueness related to inputs. The input of factors is considered as cost, quality rejection percentage, late delivery percentage, greenhouse gas emission and demand. These multiple factors are analysed to establish their weights by the fuzzy analytic hierarchy process. Then these weights are used in fuzzy multi-objective linear programming for supplier selection and quota allocation.

3. Study area and data

3.1. Study area

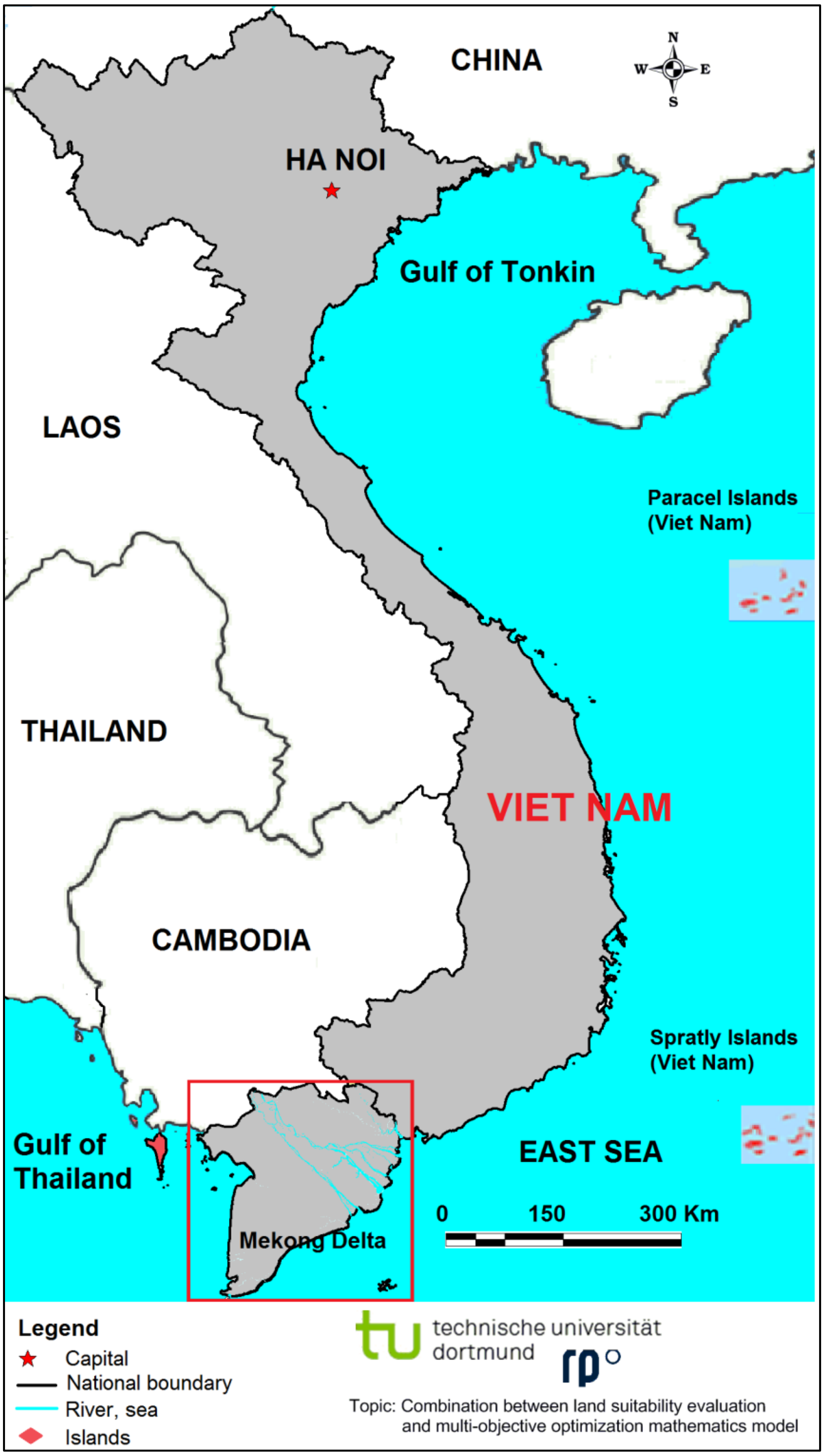


Figure 3.1.a. Location map of the Mekong Delta of Vietnam.

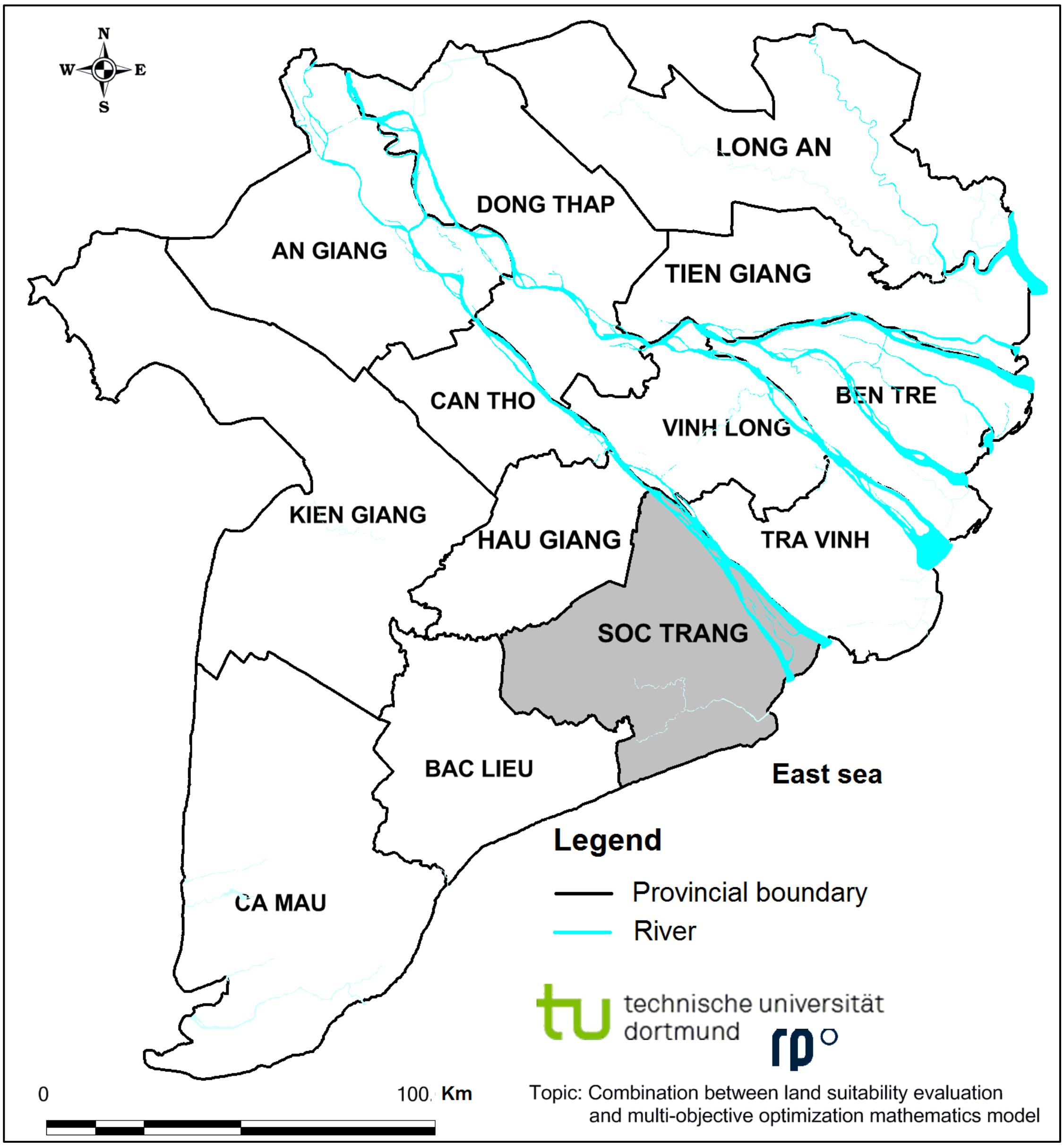


Figure 3.1.b. Location map of Soc Trang province of the Mekong Delta.

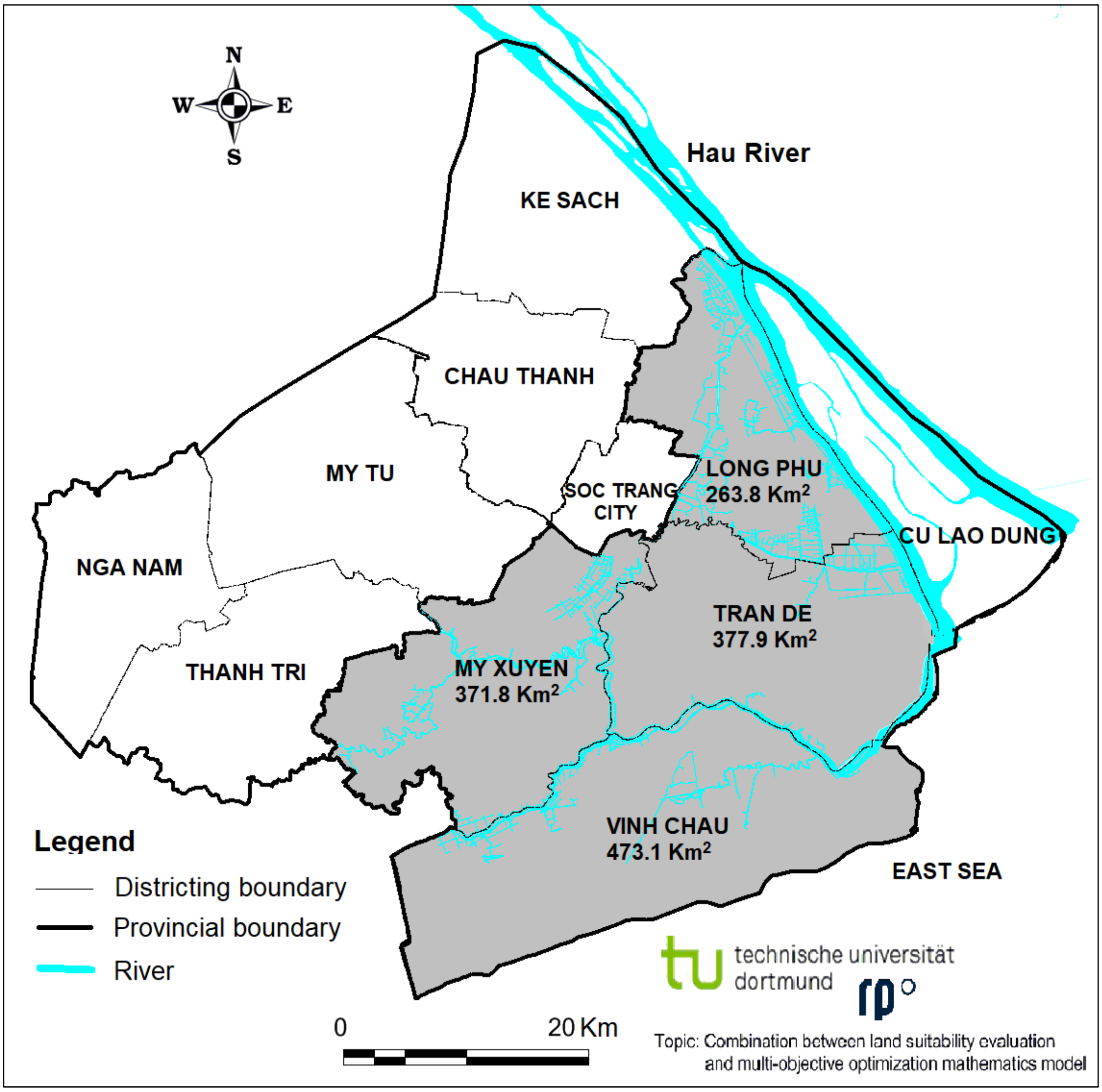


Figure 3.1.c. Location map of four coastal districts in Soc Trang province.

Soc Trang province is located in the South East of the Mekong Delta. The topography is relatively flat and low, the average height is 0.5 to 1 m above sea level, geographical coordinates are 9°14'28" to 9°55'30" north latitude; 105°34'16" to 106°17'50" east longitude. In the North-West it borders Hau Giang province, in the North-East Tra Vinh province, the South-West borders Bac Lieu province and the South-East borders the Eastern Sea (Figure 3.1.b). Soc Trang is located close to the Hau river system, which means it is easy to obtain fresh water to wash out salt from fields after the shrimp crop for the rice crop, contributing to the sustainability of the rice-shrimp model (USAID, 2016).

This study area is divided into 3 ecological zones, namely fresh, brackish and salt water. In the two last zones, shrimp-rice, extensive shrimp, semi-intensive shrimp and intensive shrimp were the major land uses (Figure 3.2). In the dry season every year, the fresh water from upstream (Mekong River) decreased significantly. The sea water flowed into river systems, mainly by Hau River. It has made increasing salt water intrusion to inland and has caused difficulties for agricultural production. Particularly, the areas in fresh water and brackish water ecological zones have declined while the area of salt water ecological zone has extended. The change is one of the main reasons which have impacted to changes in soil characteristics in four coastal districts in Soc Trang province where aquaculture has developed quickly. Shrimp and Rice Shrimp alternative cropping created high benefits for farmers. However, the density of risk was also rather more than for other types of crops. There was 20-30% failure for farmer annual; it made an unsustainable livelihood. The main problem are the changes in soil and water qualities (Kiet, 2008).

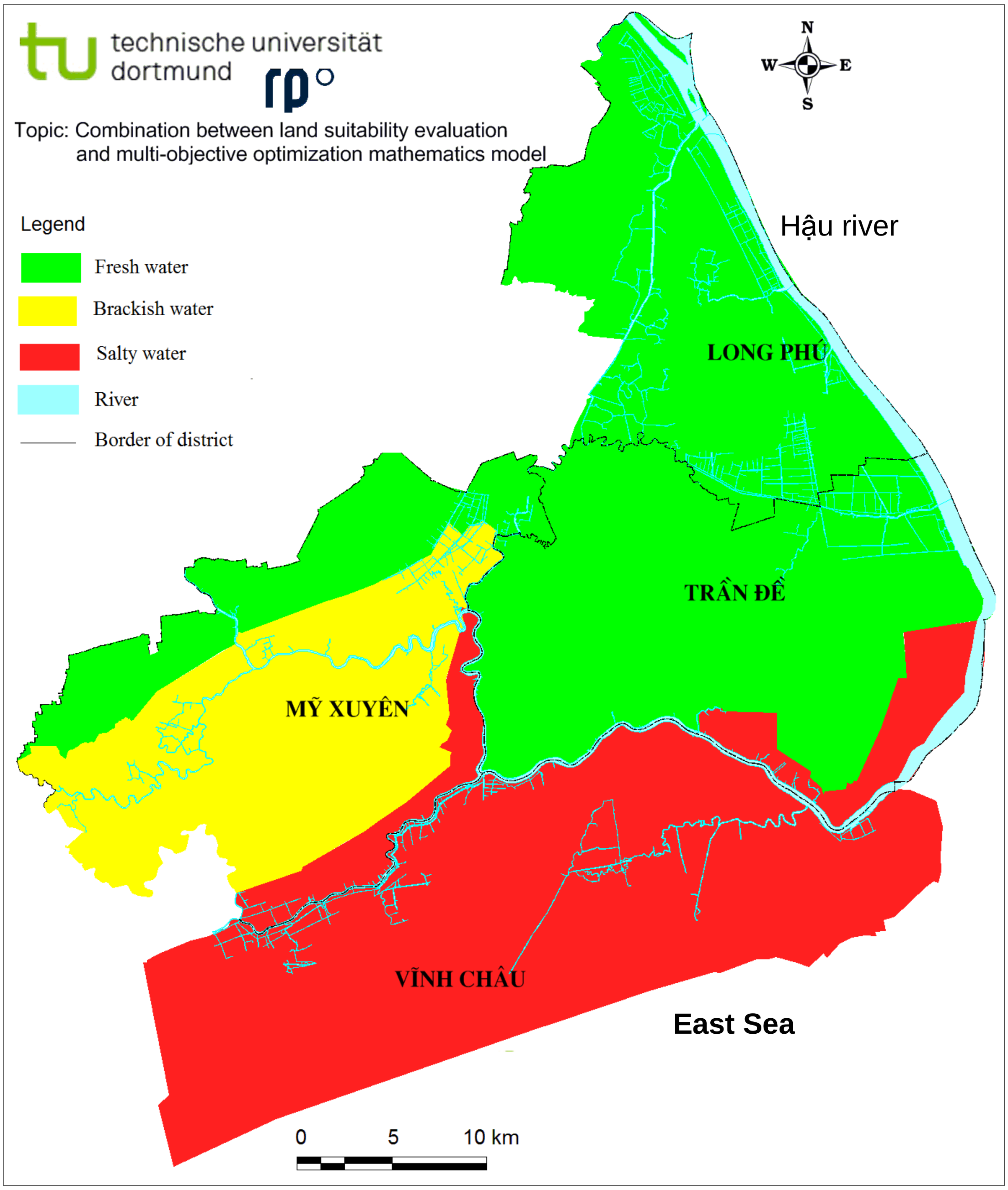


Figure 3.2. The ecological map in four coastal districts in Soc Trang province

Three ecological zones, fresh, brackish and salt water were distinguished in the coastal area of Soc Trang province. In the two last zones, shrimp-rice, extensive shrimp, semi-intensive shrimp and intensive shrimp were the significant land uses. Studying of soil and water qualities in these areas can provide necessary data for the sustainable management of shrimp ponds. The experiment was carried out by interviewing 180 farmers‘ households on their cultivation technique and income. Soil and water sampling were executed three times on three rice fields and nine shrimp ponds in the dry season. Soil and water analyses were performed to evaluate the soil and water characteristics in different farming systems (Tri et al. 2008)

In the freshwater zone, where rice was cultivated, soil pH, soil electric conductivity, cation exchange capacity (CEC) were suitable for rice growth, but soil organic matter content and available phosphorus were in the poor range.

In the shrimp systems, soil pH was low (pH of 3.9) in the shrimp-rice field at land preparation (preparing for shrimp stocking). However, at the middle stage of the shrimp cycle, soil pH, soil salinity and CEC were a favourite condition for shrimp growth. Soil nutrients such as available nitrogen, labile organic nitrogen, available phosphorus and soil organic matter content were low for food chain development in the systems. Regarding to the salinity of soils, in brackish water and salt water zones, with extensive, semi-intensive and intensive shrimp systems, soil is undergone sodification with the exchange sodium percentage (ESP) in a range of 19.22- 28.45% and the sodium adsorption ratio (SAR) was in a range of 19.42-22.49 (Table 3.2). The content of Cd and Pb in the sediment deposited in soil ponds was lower than the critical level for soil pollution (Kiet, 2008).

Table 3.1. Legend of three ecological zones as fresh, brackish and salt water in the coastal area of Soc Trang province

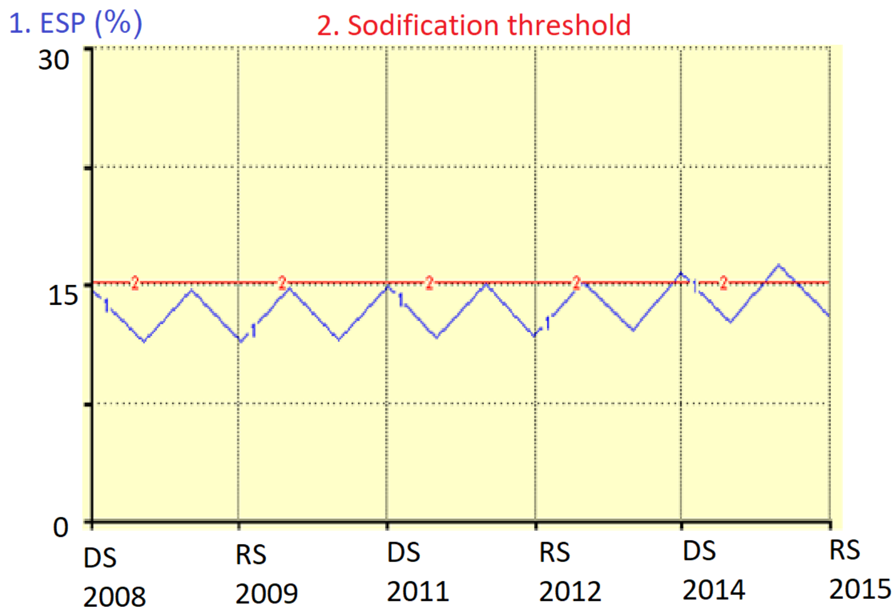
Area	Soil classification (named following World Reference Base (WRB)-FAO 2006)	Water quality		Land use present
		Salt period	Fresh period	
Fresh water	Eutric Gleysols: Gleu	None	Available	• Triple rice • Double rice
	• Hyposali Umbric Gleysols: GLumhs • Hyposali Plinthic Gleysols: GLplihs	15 December - 1 May	Available	• Double rice • Upland crop • Double rice one upland alternative crop
Brackish water	• Hyposali Eutric Gleysols: GLeuhs • Dystric Arenosols: ARd	1 January - 30 April	Available	Shrimp- Rice alternative crop
	• Hyposali Mollic Gleysols: Glmohs • Hyposali Umbric Gleysols: GLumhs	December - May	Rainy season (June-December)	Intensive shrimp
Salty water	• Sali Eutric Gleysols: GLeus • Hyposali Mollic Gleysols: Glmohs • Hyposali Umbric Gleysols: GLumhs • Dystric Arenosols: ARd • Hyposali Epi Orthi Thionic Fluvisols: FLt (oep-j)uhs	All year round	Rainy season	• Intensive shrimp • Semi-extensive shrimp • Extensive shrimp • Rice- Upland alternative crop

Table 3.2. The sodification of land utilization types in soil depths.

LUT	Soil depth (0- 20cm)		Soil depth (20- 40cm)	
	ESP (%)	SAR (%)	ESP (%)	SAR (%)
Double rice crops; Triple rice crops	9.06	10.46	10.18	12.35
Shrimp- Rice alternative crops	12.22	12.49	24.57	18.10
Extensive shrimp crops	28.45	22.49	19.22	21.11
Intensive shrimp	24.04	19.42	25.58	21.18
The second cycle of intensive shrimp	27.16	21.83	28.34	20.17

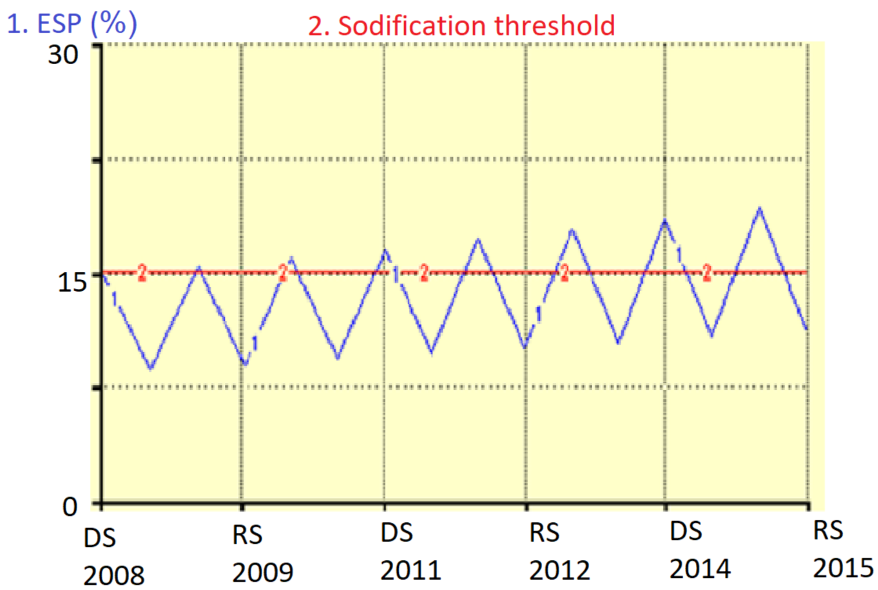
The pH, salinity and alkalinity of the water column were in a range of satisfying conditions for shrimp growth. The concentration of dissolved nitrogen (NH_4^++ NO_3^-) was low in shrimp- rice and extensive shrimp farming, but it was on a very high level in the intensive shrimp system at the end of the cycle. Dissolved phosphorus was below the sufficient level for shrimp ponds. Hydrogen sulfide was found from 0.01- 2 ppm that can cause damage to shrimp (Kiet, 2008).

Cropping patterns have been changed from double rice to shrimp-rice; extensive shrimp and intensive shrimp systems in the coastal zone of Soc Trang. The objective of this research evaluated the soil salinity and some selected water properties to provide the basic data for a better management of rice and shrimp systems. The experiment was carried out by soil and water sampling in the dry and wet season on three rice fields and nine shrimp ponds of shrimp-rice; extensive shrimp and intensive shrimp in one and two shrimp cycles from April 2006 to September 2008. Soil and water analyses were performed to evaluate the soil and water characteristics in different farming systems. The STELLA model was applied to predict the soil sodification in shrimp systems. Running the model showed that the sodification process to the dry season 2015 will be continued with ESP (Exchange Sodium Percentage) values up to 16% of 2 to 3 rice crops (Figure 3.3), 17% of shrimp – rice rotation crops (Figure 3.4), 60% of extensive shrimp (Figure 4.5) and 85% of intensive shrimp systems (Figure 3.6) (DONRE - Department of Natural Resources and Environment in Soc Trang, 2008).



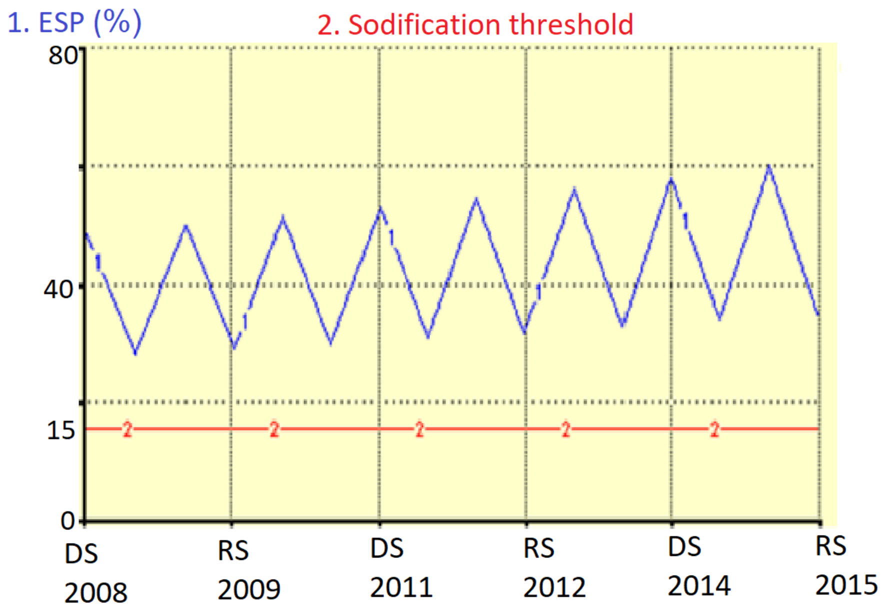
(ESP: Exchange Sodium Percentage, DS: Dry season; RS: Rainy season)

Figure 3.3. The result of soil sodification simulation of 2 to 3 rice crops.



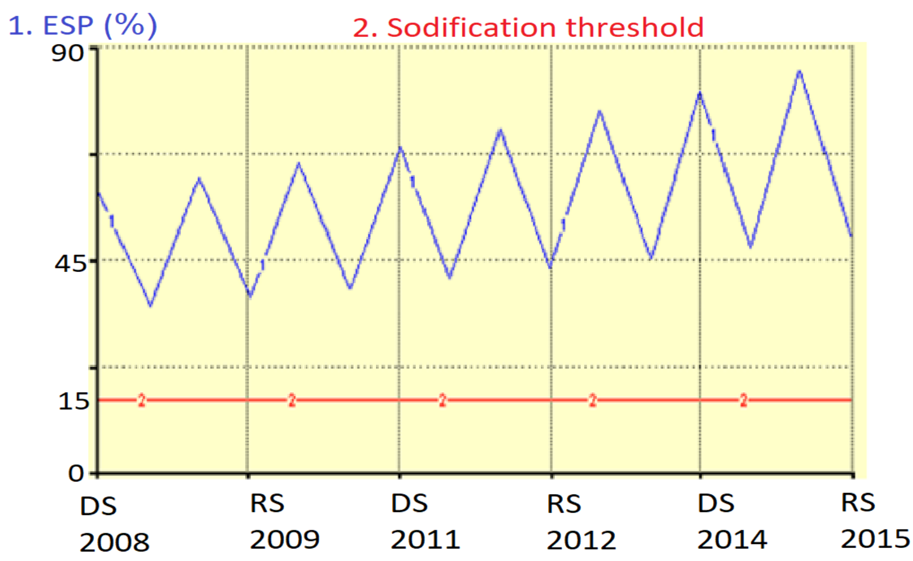
(ESP: Exchange Sodium Percentage, DS: Dry season; RS: Rainy season)

Figure 3.4. The result of soil sodification simulation of shrimp – rice rotation crops



(ESP: Exchange Sodium Percentage, DS: Dry season; RS: Rainy season)

Figure 3.5. The result of soil sodification simulation of extensive shrimp



(ESP: Exchange Sodium Percentage, DS: Dry season; RS: Rainy season)

Figure 3.6. The result of soil sodification simulation of intensive shrimp

Table 3.3 presents the land use change in four coastal districts in the time period 2000 to 2015. Land used for aquaculture increases significantly while land used for rice decreases quickly. The main reason is salt water intrusion in the dry season leading to a low harvest of the rice crop. Besides, the farmers would like the change to aquaculture crops because it brings a higher income than rice crops. The market for aquaculture products is stable (DONRE in Soc Trang, 2010; DONRE in Soc Trang, 2015).

Table 3.3. The area of agricultural land in 2000 - 2015 in four districts in Soc Trang province

Unit: Ha

No.	Land Types	2000	2005	2010	2015	2000 - 2005	2005 - 2010	2010-2015
1	Agriculture	126,287	126,901	126,749	129,180	614	-152	2,431
1.1	Production Agriculture	110,909	77,969	68,978	70,318	-32,940	-8,991	1,340
1.1.1	Cultivation of Annual Crops	95,084	66,043	56,542	57,720	-29,041	-9,501	1,178
1.1.1.1	Cultivation of Rice Crops	88,085	61,492	52,599	52,338	-26,593	-8,893	-261
1.1.1.2	Other Cultivation of Annual Crops	6,999	4,549	3,932	5,382	-2,450	-617	1,450
1.1.2	Perennial tree	15,825	11,926	12,436	12,598	-3,899	510	162
1.2	Forests	3,882	4,589	4,258	3,596	707	-331	-662
1.2.1	Production Forests	79	274	0	0	195	-274	0
1.2.2	Protection Forests	3,802	4,239	4,258	3,596	437	19	-662
1.3	Aquaculture	10,312	43,797	52,826	54,573	33,485	9,029	1,747
1.4	Salt Production	1,185	483	597	608	-702	114	11
1.5	Other of Agriculture	0	63	90	86	63	27	-4

Table 3.3 illustrates agricultural land-use changes from 2000 to 2015 in the study area. There was a clear downward trend in the area of rice crops while the opposite tendency was apparent for aquaculture. It can be divided into two distinct periods: 2000 to 2010 and 2010 to 2015. For the first period, the area of rice crops decreases significantly and stagnates in the second period 2015. A different pattern took place for the area of aquaculture. It has increased from 2000 to 2010 and after that

increased slightly to 2015. Regarding the land use change of annual crops, perennial tree and forests, there was a slight fluctuation from 2000 to 2015. Land use changes in the coastal areas in Soc Trang province have happened due to the physical settings and led to improvements of the financial income of the local farmers. The land use has been strongly changed from 2000 to 2008. The area of rice has significantly decreased whereas the intensive shrimp farming has increased.

The coastal area of Soc Trang province has been heavily influenced by climate change that affects people's livelihoods. Especially in the coastal areas, a conflict occurs between the goals of exploitation and use of natural resources through factors such as acidity, salinity, water quality and environmental problems between land use purposes. By the results of the PRA and SWOT analysis of the ecosystem, the status and the impact caused by the change and adaptation measures of the people can be assessed. The results showed that one of the measures of the people to adapt to problems connected to changing land uses in 3 different ecological zones (salt, fresh and brackish water). This solution does not require too much cost but will give a practical effect to the affected people. Ensuring a stable production and bringing economic efficiency is the primary goal (Vu et al. 2013). The semi-intensive farming model with 1-2 shrimp crops and 1 rice crop is common in Soc Trang. The semi-intensive rice-shrimp model brings higher returns than the improved extensive model, but limitations include large investment requirements, a high risk of diseases, low-quality water due to farming infrastructure, unguaranteed post larvae quality and limited capital of farmers. The improved extensive model requires lower investment but offers high efficiency, increased environmental sustainability; however, the maximum profit gained is lower than from the semi-intensive model (USAID, 2016).

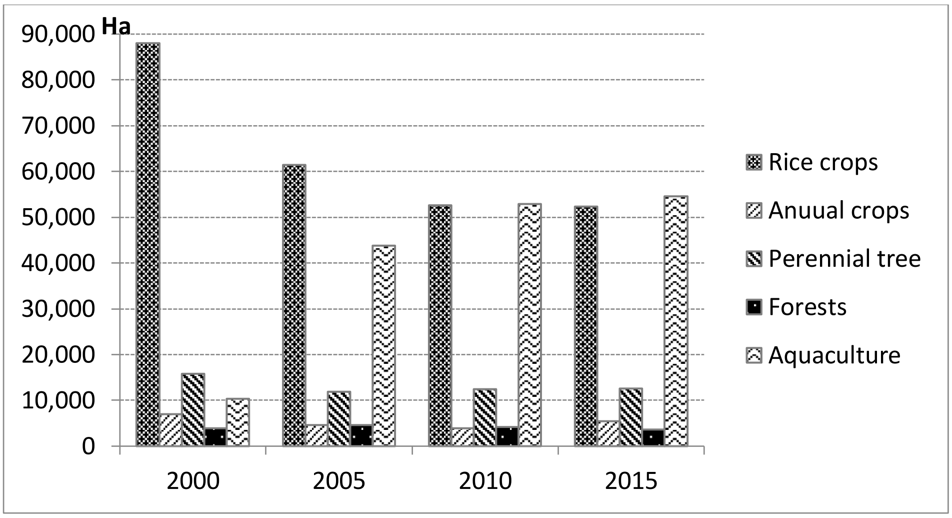


Figure 3.7. Land use change in 2000, 2005, 2010 and 2015 in four districts in Soc Trang province

Source: (DONRE in Soc Trang, 2010; DONRE in Soc Trang, 2015).

Rice-shrimp farming started in Soc Trang Province in 1992. The first form of rice-shrimp farming was stocking tiger shrimp in rice paddy fields with surrounding ditches, which were 1-1.2 m deep, accounting for 10-20 percent of the field area. Due to huge profits earned from shrimp farming, most shrimp farming ponds in Soc Trang have now been lowered 30-50 cm, and the edges are embanked higher, creating ponds with water surface depths of 0.6-0.8 m and a depth of surrounding ditches of 1.5-1.8 m. Many rice paddy fields in Soc Trang are entirely lowered without surrounding ditches like the common rice-shrimp ponds.

The rice-shrimp farming area in Soc Trang has increased rapidly, 7,929 ha in 2010, 9,919 ha in 2014, accounting for 50.2 percent of brackish water shrimp farming area in the province. By October 2015 the area was 10,271 ha. Rice-shrimp farming in My Xuyen and Vinh Chau, mostly concentrated in My Xuyen district, has 10,000 ha, accounting for 97.3 percent of the province's rice-shrimp area.

Rice-shrimp farming models include: rice-shrimp, two shrimp crops (tiger shrimp - white leg shrimp or two white leg shrimp crops) and one rice crop. Semi-intensive rice-shrimp farming is quite common in Soc Trang because households' farming areas in the province are smaller than in other provinces.

Shrimp farming takes place from February to August; rice farming from September to December. In the shrimp crop, tiger shrimp and white leg shrimp are farmed.

White leg shrimp started to be farmed in 2013, and the farming area increasing in some regions such as in Hoa Tu, where white leg shrimp farming areas accounted for 40 percent in 2013, 50 percent in 2014 and 70 percent in 2015. The tiger shrimp stocking density is 3-10 Post Larvae (PL)/m2, and “white leg” shrimp 20-50PL/m2. Giant freshwater shrimp is stocked in rice crop, at a stocking density of 5-10PL/100m2 (USAID, 2016).

Because of the trend of sea level rise, salt intrusion, longer dry seasons, shorter rainy seasons with less rainfall, cropping patterns have been changed from double rice to shrimp-rice, extensive shrimp and intensive shrimp systems. All of them quickly led to land use changes in the Soc Trang province, especially in the coastal area. This was a reason to choose the coastal area of Soc Trang including the 4 districts Long Phu, My Xuyen, Tran De and Vinh Chau for this study.

3.2. Data

In this study, a combination of quantitative and qualitative research methods was used. Both primary and secondary data were collected to answer the research questions and to address research objectives.

3.2.1. Primary data

The primary data collection includes expert interviews with local governmental staff at different levels, from province to district and commune. In addition, group and individual farmer interviews with a structured questionnaire, a household survey, were conducted.

Expert interview:

The participants are nine experts who have expertise in a certain field of activities at the Department of Natural Resources and Environment Soc Trang, the Department of Agriculture and Rural Development Soc Trang and Can Tho University. The result of the interviews established the crisp and fuzzy pair-wise comparison matrix of multi-objective analysis for two scenarios:

Scenario 1: More priority for economic and social development

Economy > Society > Environment: $Z_1 > Z_2 > Z_3 > Z_5 > Z_4$

Scenario 2: More priority for economic development and environmental protection

Economy > Environment > Society: $Z_1 > Z_2 > Z_5 > Z_4 > Z_3$

Crisp pair-wise comparison matrix for every expert:

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & 1 & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & 1 & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & 1 & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & 1 \end{bmatrix} \end{array}$$

Where:

Z_1 : The maximize Income function (Million VND/ha/year)

Z_2 : The maximize Benefit per cost ratio (B/C) function

Z_3 : The maximize Employment function (day)

Z_4 : The maximize highly suitable area of land physical suitability (ha)

Z_5 : The maximize protect the environment

a_{12}, a_{13}, …, a_{54}: Value of linguistic scale from 1 to 9. (1: Equal importance; 3: Weak importance; 5: Essential or strong importance; 7: Very strong importance; 9: Extremely preferred; 2,4,6,8: Intermediate)

The Consistency Ratio (CR) of the pair-wise comparison matrix is a measure of how much difference there is. It will be accepted and must be less than or equal to 0.1. If the Consistency Ratio is greater than 0.1, the pair-wise comparisons matrix should be recalculated.

Group farmer interview:

Participatory Rural Appraisal (PRA) method: There were 5 groups in the 5 representative communes of the study areas. Group sizes ranged from 10 to 15 peoples considering gender equally. The group discussion was carried out for a general understanding of socio-economic conditions and details of the salinity intrusion problem as well as land use change in the study areas. More details are as follows (Table 3.4 and Figure 3.8):

• Identify the factors which led to a change of land use types (LUTs) from 2000 to 2010.

• The economic effects in the present agricultural production.

• The analysis SWOT (Strengths, Weaknesses, Opportunities, Threats) that influence the present agricultural production.

Individual farmer interviews:

Household survey: The household survey was conducted after the Participatory Rural Appraisal (PRA) method on 2014. There are 139 households at the five communes in 4 coastal districts participating in the survey using a structured questionnaire. The participating households were selected randomly, as follows (Table 3.4 and Fig. 3.8):

Table 3.4. Distribution of group and individual farmer interviews at different levels

Level	**Name of location**	**Number of Group farmer**	**Number of the individual farmer**
District	Long Phu	1	
	My Xuyen	1	
	Tran De	1	
	Vinh Chau	2	
Commune	Truong Khanh		31
	Tai Van		30
	Ngoc Dong		23
	Khanh Hoa		29
	Phuong 2		26
	Total	5	139

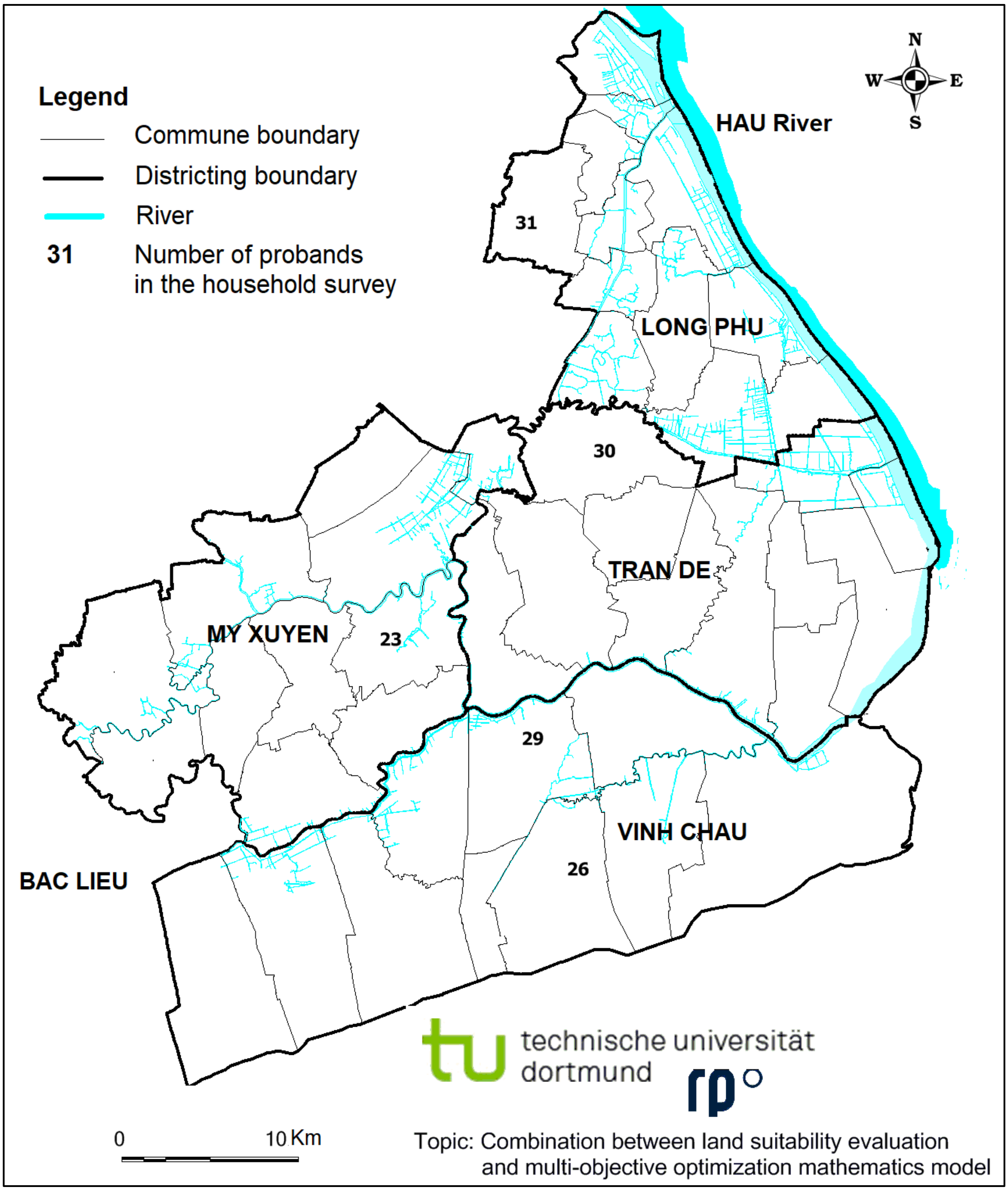


Figure 3.8. Spatial distribution of household survey and number of probands

- LUT 1 (Three rice crops): 31 households
- LUT 2 (Two rice crops): 30 households
- LUT 3 (Shrimp – Rice rotation crops): 23 households
- LUT 4 (Shrimp crop): 29 households
- LUT 5 (Rice – Upland rotation crops): 26 households

3.2.2. Secondary data

The secondary data were gathered from different sources and organisations (Table 3.5):

Table 3.5. Secondary data

	Data	Date	Description
Spatial data (GIS data)	Present land use	2000, 2005, 2010 2015	Department of Natural resources and Environment in SocTrang province
	Soil	2013	Department of Land resources, the College of Environment and Natural Resources, Can Tho University
	General socio-economic planning	2020	Department of Natural resources and Environment in SocTrang province
	Land use planning	2020	Department of Natural resources and Environment in SocTrang province
	Agricultural land use planning	2020	Department of Agriculture and Rural development, SocTrang province
Non-spatial data	Demographic, socio-economic, land use	2000, 2005, 2010, 2015	Local bureau of statistics in district and province level. Statistical yearbooks of the Viet Nam General Statistics Office. The Viet Nam Ministry of Natural Resources and Environment.
	Agricultural production and management. Farmland capability. Environment. Meteorology and hydrology.		Local departments of agriculture and rural development in SocTrang province.

4. Methodology

4.1. Land suitability analysis in the crisp environment

4.1.1. Land evaluation (FAO, 1976)

Selection of land use types (LUTs) for land evaluation. Selecting the type of land use to evaluate the suitability of land was based on:

Surveying the actual state of land use in the study area.

The development objectives of the local government.

Promising farming systems.

Requirements of food consumption and commodity.

Apparent agro-climate suitability.

Market orientation.

The results of previous research on land use systems in the area concerned.

Besides, social-economic considerations play an essential role in the process of selection as well as in the description of LUTs in terms of social-economic and technical management and infrastructure attributes.

Identification of land quality and diagnostic factors of land use types (LUTs):

The land quality and the diagnostic factors are determined for each land use type on the land mapping units. The land quality that has been selected directly impacts the ability to adapt to each land use type.

Conducting land use requirements:

Land use requirements are based on the form and basis of land quality for each land use type that is determined for each type of land use. The factor rating of each land use type is based on (FAO, 1976) that is classified into four levels highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and none suitable N).

Matching to present land suitability classification:

Land characteristics were suggested by experts in soil science and land suitability. A real survey and interviews of farmers are needed to establish land characteristic maps, to overlay these maps and to establish land mapping units. Based on land qualities are described by the diagnostic factors of each land use type in the land mapping units, that is conducted for a comparison with other land use requirements of each land use type described by a factor rating for each land unit map. Appropriate land classification is based on the classification table structure adapted from FAO (1976) with four levels: order, classes, sub-classes and units. In this study, the sub-class level was used for land suitability classification.

Upgrading suitability classification:

Based on present land suitability, a large number of land units will not adapt to the appropriate average for the land mapping units (LMUs). Based on these limiting factors reducing the level of suitability, it is undertaken to adopt technical measures to improve the soil quality for upgrading. Results of upgrades are adapted as a basis for the improvement of investment and the application of the proposed land use patterns suitable for different areas.

Land suitability zoning:

On the basis of the classification of land suitability for land use types (LUT) for land mapping units, the establishment of a similar level of adaptation after the upgrade of LMUs is conducted to form regions with the same level of adaptation. In Addition, the proposed land use types have a high adaptability and feasibility for adaptation to each region as a basis for land use planning.

4.1.2. Multi criteria decision analysis

MCE is a quantitative analytic of factors and to calculate the average:

$$S_i=\sum w_i * X_i \tag{4.1}$$

w_i: weight of land characteristic, identified by interviewed farmers, $w_i \in [0,1]$

X_i: suitability value of land characteristic for every LUT, identified by interviewed farmers. X_i [0,10]

It was calculated and assigns the suitability level S_i.

S_i: Suitability level of LUTs standardized according to FAO (1976),

- None suitable (N): $X_i \in [0,2]$
- Marginally suitable (S_3): $X_i \in (2,4]$
- Moderately suitable (S_2): $X_i \in (4,8]$
- Highly suitable (S_1): $X_i \in (8,10]$

4.2. Land suitability analysis in the fuzzy environment

To define the membership function of X_i (μ(x)):

Triangular fuzzy membership functions are the approximations of real-life curves. Therefore, it takes into account the real-world scenario (Susanto & Bhattacharya, 2011). The fuzzy sets theory was introduced into the developed model to deal with fuzziness. To deal with fuzzy problems, membership functions such as the triangle linear function were often used (Ren et al. 2017). In this study, the triangle linear function was selected. Triangular fuzzy numbers could quantify the most important information about a fuzzy number as the upper bound, lower bound and the most possible value. Fuzzification via membership functions for 4 linguistic terms of suitable level (S1, S2, S3, N) by triangular fuzzy number.

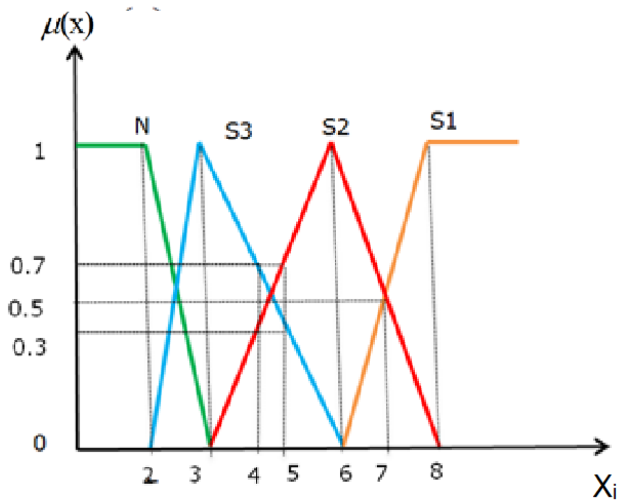


Figure 4.1. Fuzzification via membership functions for 4 linguistic terms of suitable level (S1, S2, S3, N)

Reclassify X_i by 4 levels of suitability, $X_i \in [0,10]$ and fuzzification via membership functions for 4 linguistic terms of suitable level (S1, S2, S3, N) (Figure 4.1).

Fuzzy union method:

Fuzzy union of the characteristic maps by the algorithm

$$S = (w°R)°C^i = \left([w_1 w_{2...} w_n]° \begin{bmatrix} \mu_{11}(x) & \mu_{12}(x) & \mu_{13}(x) & \mu_{14}(x) \\ \mu_{21}(x) & \mu_{22}(x) & \mu_{23}(x) & \mu_{24}(x) \\ ... & ... & ... & ... \\ \mu_{n1}(x) & \mu_{11n2}(x) & \mu_{1n3}(x) & \mu_{n4}(x) \end{bmatrix} \right) °C^i \quad (4.2)$$

S: the suitability matrix

w: weight of land characteristic

R: the fuzzy relative matrix

C^i: The logic value of limit factors of LUT (Yes = C^1 /or No = C^0)

μ_{ij} (x) : the membership of land characteristic i (i- 1,2, …, n) of the suitability level (j = 1,2,3,4 represent S_1 , S_2 , S_3 , N respectively)

o: Fuzzy operator by MAX: $\mu_{A\cup B}(x) = \text{Max}\{\mu_A(x), \mu_B(x)\}$

o: Fuzzy operator by LUKASIEWICZ $\mu_{A\cup B}(x) = \text{Min}\{1, \mu_A(x) + \mu_B(x)\}$

It was calculated by two fuzzy operators above and to identify the suitability level by the maximum value of the membership.

4.3. Fuzzy multi-objective linear programming (FMOLP)

One of the essential tasks of spatial planning is the evaluation of the decision making process of how to use available land, so five objects for fuzzy multi-objective linear programming (FMOLP) were identified, such as: Maximize Income (Z1); Maximize Benefit per cost ratio- B/C (Z2); Maximize Employment (Z3); Maximize highly suitable area of land physical suitability (Z4); Maximize protect environment (Z5). It will solve three main problems in the economy, society and environment for sustainable agricultural land use planning, but it dealt with four main constraint functions such as (i) Land physical suitability area, (ii) agricultural land area; (iii) Available agricultural labor force; (iv) Cost.

Agricultural land use planning involves the assessment of land potential as well as land requirements for various LUTs to identify the optimum land unit for each type, then to identify variables for the objective function.

X_{ijk} : Agricultural land use type- LUT (ha),

Where:

i (i = 1, 2, ..., 5): number of variables depending on LUT

j: Suitability levels S1 (High suitability), S2 (Moderate suitability) and S3 (j = 1, 2,3) from result land physical suitability

k: Land suitability areas (k = 1, 2, .., 13). It was formulated from the result of land physical suitability.

$b_{ijk(l)}$: coefficients of the objective function, (l =1,2,3,4,5).

Objective functions:

The maximize Income function: Z_1 (Million VND/ha/year)

$$Z_1 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(1)} X_{ijk} \rightarrow Max \qquad (4.3)$$

The maximize Benefit per cost ratio (B/C) function: Z_2

$$Z_2 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(2)} X_{ijk} \rightarrow Max \qquad (4.4)$$

The maximize Employment function: Z_3 (day)

$$Z_3 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(3)} X_{ijk} \rightarrow Max \qquad (4.5)$$

The maximize highly suitable area of land physical suitability: Z_4 (ha)

$$Z_4 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(4)} X_{ijk} \rightarrow Max \qquad (4.6)$$

The maximize protect environment : Z_5

$$Z_5 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(5)} X_{ijk} \rightarrow Max \qquad (4.7)$$

$b_{ijk(5)}$: fuzzy environmental protection coefficient. It was formulated by % interviewer's opinion (Good, Rather good; Fair; Poor) for every LUT as a statistic of γ_i., which it is only qualitative and needs to be changed to quantitative data. Therefore, every level (%) will be assigned a number. E.g. Good = 100; Rather good = 75; Fair = 50; Poor = 25). By the way, identify expectation m_i

Establish multi-objective function

Interactive fuzzy satisfying method (Sakawa, 2002):

1. Calculate the individual minimum and maximum of each objective function under the given constraints by solving the following problems;

2. By considering the individual minimum and maximum of each objective function, the decision maker subjectively specifies membership functions $\mu_l(f_l(X))$, l = 1,2,…,k, to quantify fuzzy goals for objective functions;

3. The decision maker sets initial reference membership levels μ_l, l= 1,2,…,k;

4. For the current reference membership levels, solve the augmented max problem to obtain the M-Pareto optimal solution and the membership function value;

5. If the decision maker is satisfied with the current levels of the M-Pareto optimal solution, stop. Then the current M-Pareto optimal solution is the satisfying solution of the decision maker. Otherwise, ask the decision maker to update the current reference membership levels μ_l, l= 1,2,…,k, by considering the current values of the membership functions and return to 4.

Firstly, using Module Solver in Microsoft Excel run for every single objective Z_1, Z_2, Z_3, Z_4, Z_5, Z_6 with the similar constraints. The result showed that 6 scenarios X^1, X^2, X^3, X^4, X^5, X^6

Establish Pay - Off table, identify upper Z_i^B, and lower bounds Z_i^w of 5 objectives Z_1, Z_2, Z_3, Z_4, Z_5 ,where $Z_i^B = Z_i(X^i)$ and $Z_i^w = Min\{Z_i(X^j): j = 1, 2, \ldots, 5\}$.

Interactive fuzzy satisfying for every objective $\mu_i(Z_i)$

$$\mu_i(Z_i) = \frac{Z_i - Z_i^w}{Z_i^B - Z_i^w} \quad (4.8)$$

i = 1,2,3,4,5

$$u = w_1\,\mu_1(Z_1) + w_2\,\mu_2(Z_2) + w_3\,\mu_3(Z_3) + w_4\,\mu_4(Z_4) + w_5\,\mu_5(Z_5) \quad (4.9)$$

Where w_1, w_2, w_3, w_4, w_5 : weights

$$w_1 + w_2 + w_3 + w_4 + w_5 = 1 \text{ and } 0 \le w_1, w_2, w_3, w_4, w_5 \le 1.$$

The next step applies Analytic Hierarchy Process (AHP) and Fuzzy Analytic Hierarchy Process- Group Decision Making (FAHP-GDM) methods to identify weights.

4.4. The Fuzzy Analytic Hierarchy Process- Group Decision Making (FAHP-GDM)

Fuzzy AHP has been playing an increasingly important role in multiple criteria decision-making under uncertainty and has found extensive applications in a wide variety of areas such as supplier selection. The use of Fuzzy Analytic Hierarchy Process (FAHP) for multiple criteria decision-making requires scientific weight derivation from fuzzy pairwise comparison matrices (Figure 4.2).

The analytic hierarchy process has been used in many different fields as a multi-attribute decision analytic tool with multiple alternatives and criteria. AHP uses “pair-wise comparisons” and matrix algebra to weight criteria. The decision is made by using the derived weights of the evaluative criteria. Importance is measured on an integer-valued 1 - 9 scale, with each number having the interpretation shown in Table 4.1 (Saaty, 2008).

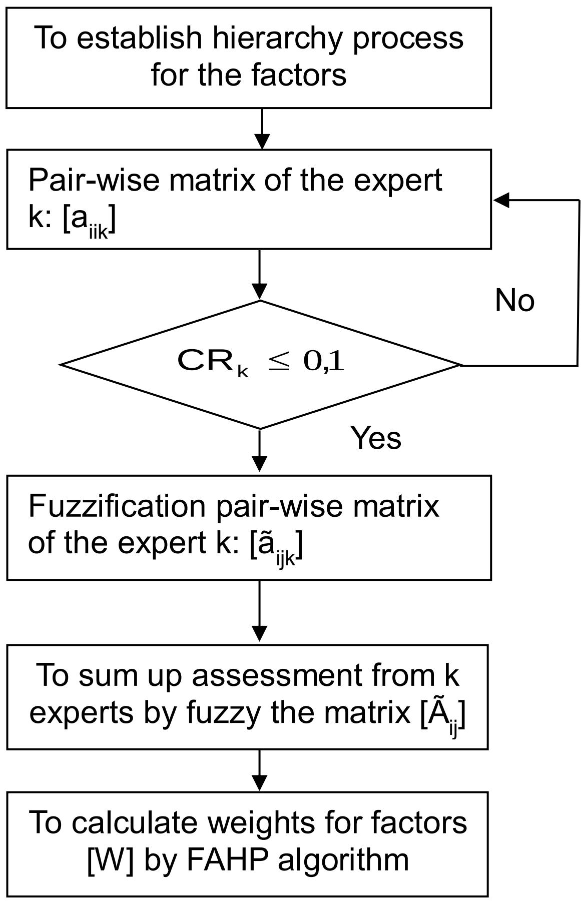


Figure 4.2. The Fuzzy Analytic Hierarchy Process- Group Decision Making (FAHP-GDM) Method to identify weights

AHP includes a consistency index for an entire hierarchy, and therefore it is necessary to consider whether the pair-wise comparison has been consistent at each level in the hierarchy, to accept the results of weighting, or to investigate the problem and revise judgments. The Consistency Ratio (CR) indicates how much variation is allowed for weighted results. A higher value (number) means less consistency, whereas a lower value (number) means that there is more consistency in judgments of the pair-wise comparison matrix. The CR is expected to be less than 10 percent because it implies that the judgment is small compared to the actual values of the eigenvector entries (Saaty and Vargas, 2001).

Variable and fuzzy value in comparative study: Based on the original of the relative importance between two criteria in crisp value Saaty (2008), Srdjevic & Medeiros, (2008) and Önüt, Efendigil, & Soner Kara, (2010), described linguistic scale with the fuzzy values of linguistic variables (the triangular fuzzy conversion and triangle fuzzy reciprocal scale) in pair-wise (Table 4.1).

Table 4.1. Variable and fuzzy value in comparative study

Saaty´s crisp value	**Linguistic scale describing the relative importance between two criteria**	**Triangle fuzzy conversion scale** ***(l, m, u)***	**Triangle fuzzy reciprocal scale** ***(1/u, 1/m,1/l)***
	Just equal	(1, 1, 1)	(1, 1, 1)
1	Equal importance	(1, 1, 2)	(1/2, 1, 1)
3	Weak importance	(2, 3, 4)	(1/4, 1/3, ½)
5	Essential or strong importance	(4, 5, 6)	(1/6, 1/5, ¼)
7	Very strong importance	(6, 7, 8)	(1/8, 1/7, 1/6)
9	Extremely preferred	(8, 9, 9)	(1/9, 1/9, 1/8)
2, 4, 6, 8	Intermediate	(x-1, x, x+1) x=2, 4, 6, 8	(1/(x+1), 1/x, 1/(x-1)) x=2, 4, 6, 8

Triangular fuzzy numbers: Saaty (2008) contended that the geometric mean accurately represents the consensus of experts, and is the most widely used in practical applications (Bellmann & Zadeh, 1970). Here, geometric mean (which represents the consensus of experts) is used as the model for triangular fuzzy numbers that is the mean of membership = 1. Where U denotes the minimum numerical value and L is the geometric mean, which represents the consensus of most experts. Therefore, the values within L and U represent the possibilities for a different consensus (Figure 4.3). Since each number in the pair-wise comparison matrix represents the subjective opinion of decision makers and is an ambiguous concept, fuzzy numbers work best to consolidate fragmented expert opinions. To sum up, the assessment from k experts by the establishment of triangular fuzzy number $\widetilde{A}_{ij}$ as follows (Chang et al. 2009):

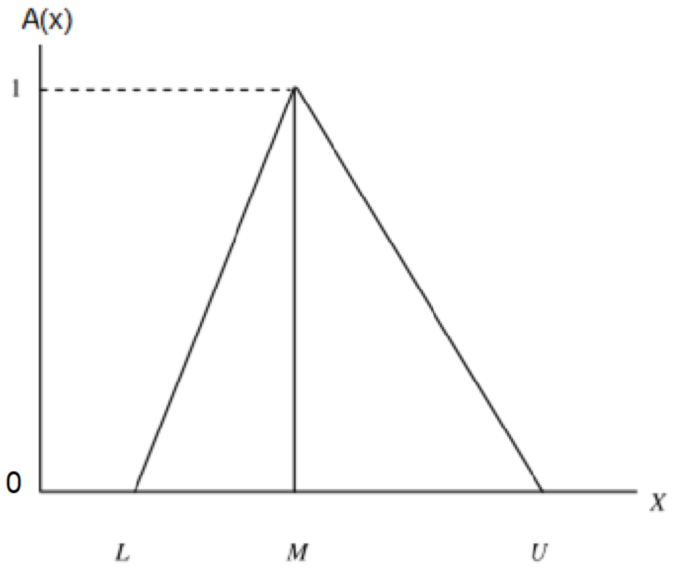


Figure 4.3. Triangular fuzzy numbers

A triangular fuzzy number is represented by lower value l, mean value m, and upper value u, i.e., (l,m,u). The membership function is given by:

$$\mu(x) = \begin{cases} \frac{x}{m-l} - \frac{l}{m-l} & x \in [l,m] \\ \frac{x}{m-u} - \frac{u}{m-u} & x \in [m,u] \\ 0 & \text{Otherwise} \end{cases} \tag{4.10}$$

Let $(l_1,\ m_1,\ u_1)$ and $(l_2,\ m_2,\ u_2)$ be two triangular fuzzy numbers. Then the basic fuzzy arithmetic operators can be described as follows:

Addition

$$(l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{4.11}$$

Multiplication

$$(l_1, m_1, u_1) \circledast (l_2, m_2, u_2) = (l_1\, l_2, m_{1,} m_2, u_1 u_2) \tag{4.12}$$

Scalar multiplication

$$\lambda \circledast (l_1, m_1, u_1) = (\lambda l_1\ , \lambda m_{1,}, \lambda u_1) \tag{4.13}$$

Inverse

$$(l_1, m_1, u_1)^{-1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right) \tag{4.14}$$

Crisp pair-wise comparison matrix :

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ \dots \\ Z_I \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & \dots & Z_i \end{array} \\ \begin{bmatrix} 1 & a_{12} & a_{13} & \dots & a_{1i} \\ a_{21} & 1 & a_{23} & \dots & a_{2i} \\ a_{31} & a_{32} & 1 & \dots & a_{3i} \\ \dots & \dots & \dots & 1 & \dots \\ a_{i1} & a_{i2} & a_{i3} & \dots & 1 \end{bmatrix} \end{array}$$

$$\widetilde{A}_{ij} = (L_{ij}, M_{ij}, U_{ij}), \tag{4.15}$$

$L_{ij} \le M_{ij} \le U_{ij}$ and L_{ij}, M_{ij}, $U_{ij} \in [1/9, 1] \cup [1,9]$ (4.16)

Where $L_{ij} = \min(l_{ijk}), M_{ij} = \left(\prod_{k=1}^{n} m_{ijk}\right)^{1/n}, U_{ij} = \max(u_{ijk})$

u_{ijk} represents a judgment of expert k for the relative importance of two criteria i–j.

l,m,u represents triangle fuzzy scale.

Table 4.2. Fuzzy pair-wise comparison matrix from summing up k experts

Z_1			**Z_2**			**Z_3**			**…..**	**Z_j**		
1	**1**	**1**	l_{12}	m_{12}	u_{12}	l_{13}	m_{13}	u_{13}		l_{1j}	m_{1j}	u_{1j}
l_{21}	m_{21}	u_{21}	**1**	**1**	**1**	l_{23}	m_{23}	u_{23}		l_{2j}	m_{2j}	u_{2j}
l_{31}	m_{31}	u_{31}	l_{32}	m_{32}	u_{32}	**1**	**1**	**1**		l_{3j}	m_{3j}	u_{3j}
…..												
l_{i1}	m_{i1}	u_{i1}	l_{i2}	m_{i2}	u_{i2}	l_{i3}	m_{i3}	u_{i3}		**1**	**1**	**1**

To calculate weights for factors [W] by FAHP algorithm.

According to Chang´s (1992) extent analysis method:

First, the outlines of the extent analysis method on fuzzy AHP are given, and then the method is applied to a catering firm selection problem. Let X= {x_1, x_2, …, x_n) be an object set and U= {u_1, u_2, …, u_m} be a goal set. According to the method of Chang's (1992) extent analysis, each object is taken and extent analysis for each goal, g_i, is performed, respectively. Therefore, m extent analysis values for each object can be obtained, with the following signs:

$$M^1_{gi},\ M^2_{gi},\ \ldots,\ M^m_{gi} \qquad i = 1,2,\ldots,n \tag{4.17}$$

$M^j_{gi}(i = 1, 2, ..., n; j = 1, 2, ..., m)$ are triangle fuzzy numbers.

The steps of Chang's extent analysis can be given as in the following:

1. The value of fuzzy synthetic extent with respect to i, the object is defined as:

$$S_i = \sum_{j=1}^{m} M^j_{gi} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} \right]^{-1} \tag{4.18}$$

To obtain $\sum_{j=1}^{m} M^j_{gi}$ perform the fuzzy addition operation of m extent analysis values for a particular matrix such that

$$\sum_{j=1}^{m} M^j_{gi} = \left(\sum_{j=1}^{m} l_j,\ \sum_{j=1}^{m} m_j,\ \sum_{j=1}^{m} u_j \right) \tag{4.19}$$

Moreover, to obtain $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} \right]^{-1}$ perform the fuzzy addition operation of $M^j_{gi}(i = 1, 2, ..., n; j = 1, 2, ..., m)$ values such that

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} = \left(i = \sum_{i=1}^{n} l_i,\ \sum_{i=1}^{n} m_i,\ \sum_{i=1}^{n} u_i \right) \tag{4.20}$$

Moreover, then compute the inverse of the vector in Eq. (4.20) such that

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{4.21}$$

2. The degree of possibility of

$M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as

$$V(M_2 \geq M_1) = \sup_{y \geq x} [\min(\mu_{M_1}(x), \mu_{M_2}(y))] \tag{4.22}$$

And can be equivalently expressed as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1, \text{if } m_2 \geq m_1 \\ 0, \text{if } l_1 \geq u_2 \\ \text{else}: \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \end{cases} \tag{4.23}$$

Where d is the ordinate of the highest of the intersection point d between μ_{M_1} and μ_{M_2} (Figure 4.4)

To compare M_1 and M_2, we need both the values of the $V(M_2 \geq M_1)$ and $V(M_2 \leq M_1)$.

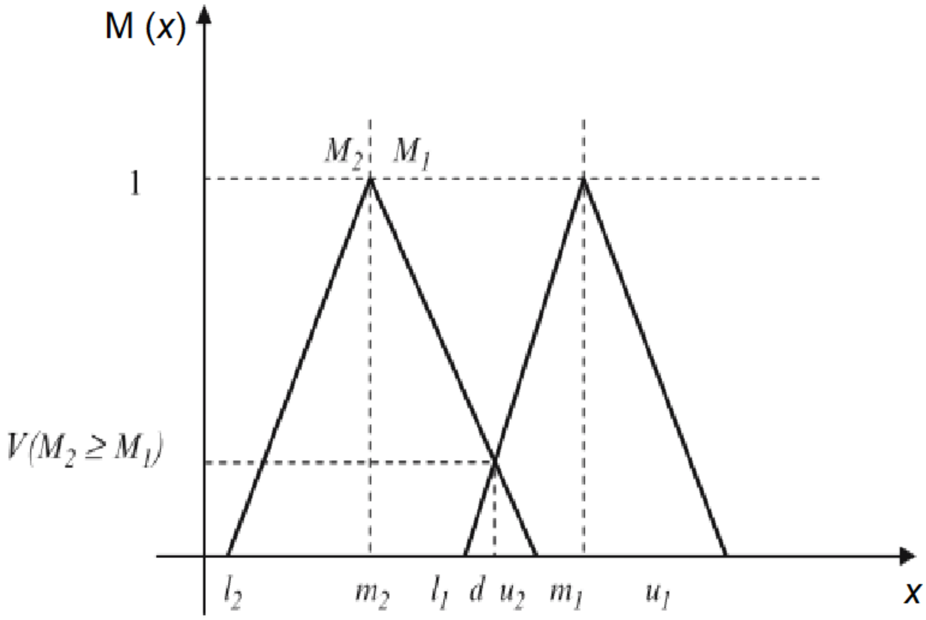


Figure 4.4. The intersection between M_1 and M_2

3. The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i = (i = 1,2,…,k) can be defined by

$$V(M \geq M_1, M_2, ..., M_k) = V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and...and } (M \geq M_k)]$$
$$= \min V(M \geq M_i), \text{ i = 1, 2, …, k} \quad (4.24)$$

Assume that

$$d'(A_i) = \min V(S_i \geq S_k), \quad (4.25)$$

For k = 1,2,…,n; k ≠ i. Then the weight vector is given by

$$[W'] = [d'(A_1), d'(A_2), ..., d'(A_n)]^T \quad (4.26)$$

Where A_i(i = 1,2,…,n) are n elements.

4. Via normalization, the normalized weight vectors are

$$[W] = [d(A_1), d(A_2), ..., d(A_n)]^T \quad (4.27)$$

Where: W is a nonfuzzy number.

5. Result and discussion

5.1. The indicators of natural resources and weights in the crisp and fuzzy environment

The process of land evaluation includes:

Identifying, selecting and describing appropriate LUTs for the area under consideration.

The interview results show that LUT selection is based on local governmental development objectives, current land use, promising farming systems, requirements of food consumption and food commodity, apparent agro-climatic suitability, and market orientation. Socio-economic considerations also play an essential role in the selection process in the study area. There are 5 LUTs that are selected.

The cropping calendar of LUTs can be divided into some main groups as follow:

LUT 1 (3 Rice crops): The 1st crop named Summer - Autumn (from May to August), the 2nd crop named Autumn - Winter (from October to January of next year) and the 3rd crop named Winter-Spring (from January to April).

LUT 2 (2 Rice crops): The 1st crop named Summer - Autumn (from May to August) and the 2nd crop named Autumn – Winter (from October to January of next year).

LUT 3 (Shrimp – Rice rotation crops): On the dry season (from January to May) when having salt water intrusion, shrimp crop is cultured. The following one is on the rain season (from July to November) when there is fresh water, rice crop is cultured.

LUT 4 (Shrimp crop): There are two to three shrimp crops that are cultured for a whole year in the salt water zone.

LUT 5 (Rice – Upland rotation crops): On the rain season (from July to November), the rice crop is cultured. The following dry season (from January of next year to May), the upland crop (onion, chilli, beet, corn) is cultured.

Conducting land use requirements:

To evaluate land suitability for LUTs in the study area, a division by land units with seven land characteristic maps (Figure. 5.1.a, 5.1.b, 5.1.c, 5.1.d) is needed. These land characteristics were suggested by experts in soil science and land suitability, such as: Soil type, depth of sulphuric horizon, soil texture, salty time, salinity, flooding time, depth of flooding. A real survey and interviews of farmers are needed to make seven characteristic maps, to overlay these maps and to establish land unit mapping

There are thirty LMUs and five land use types (LUTs) in the studied area. For each LMU, five alternatives LUT were evaluated. The LMUs were identified by land characteristics: Soil type, depth of sulphuric horizon (cm), soil texture, salty time (months), salinity (‰), flooding time (days) and depth of flooding (cm). The result of LMUs and their characteristics are shown in Figure 5.2 and Table 5.1.

1. Soil type: It was classified by World Reference Base/ Food Agriculture Organization (WRB/FAO) (2006) classification system. There are 10 soil types in study areas:

1) Dystric Arenosols: ARd,

2) Salic Eutri Gleyic Fluvisols: Flegs,

3) Salic Eutric Fluvisols: FLeus,

4) Hyposali Epi Orthi Thionic Fluvisols: FLt (oep-j)uhs,

5) Eutric Gleysols: Gleu,

6) Hyposali Eutric Gleysols: GLeuhs,

7) Sali Eutric Gleysols: GLeus,

8) Hyposali Mollic Gleysols: GLmohs,

9) Hyposali Plinthic Gleysols: GLplihs,

10) Hyposali Umbric Gleysols: GLumhs.

2. The depth of sulphuric horizon (cm): The toxins in the sulphuric soil are compounds of iron (Fe), aluminium (Al) and sulphate (SO_4^{2-}). It was caused

by toxic plants and aquatic animals. It was surveyed from land surface; there are two levels: 0 and 50 – 80 cm.

3. Soil texture: There are 4 soil texture types: Sandy loam, clay loam, loam, silt loam.

4. Salty time (months): Because of topography and ecological features, the research area was salty over time such as: None, 1, 4, 6, 8, 10, 12 months.

5. Salinity (‰): The salinity in water was identified by the levels: None, 4- <8, 8 - <12, 12 – 25 (‰).

6. The flooding time (days): None, 5- 7 days.

7. Depth of flooding (cm): None, < 30, 30- 60 cm.

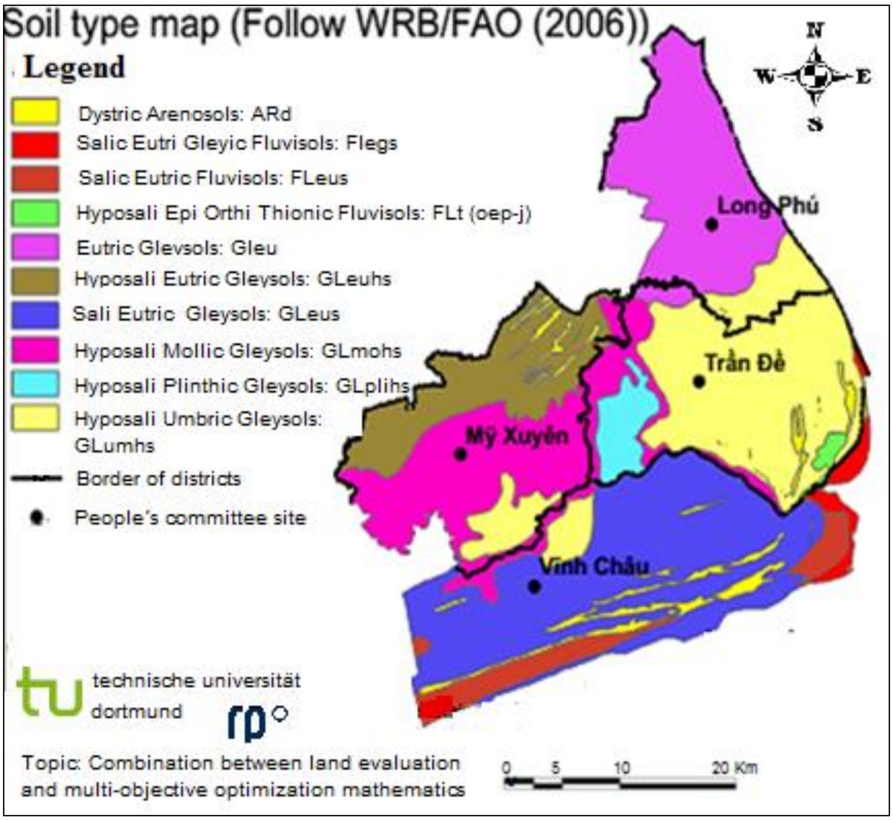
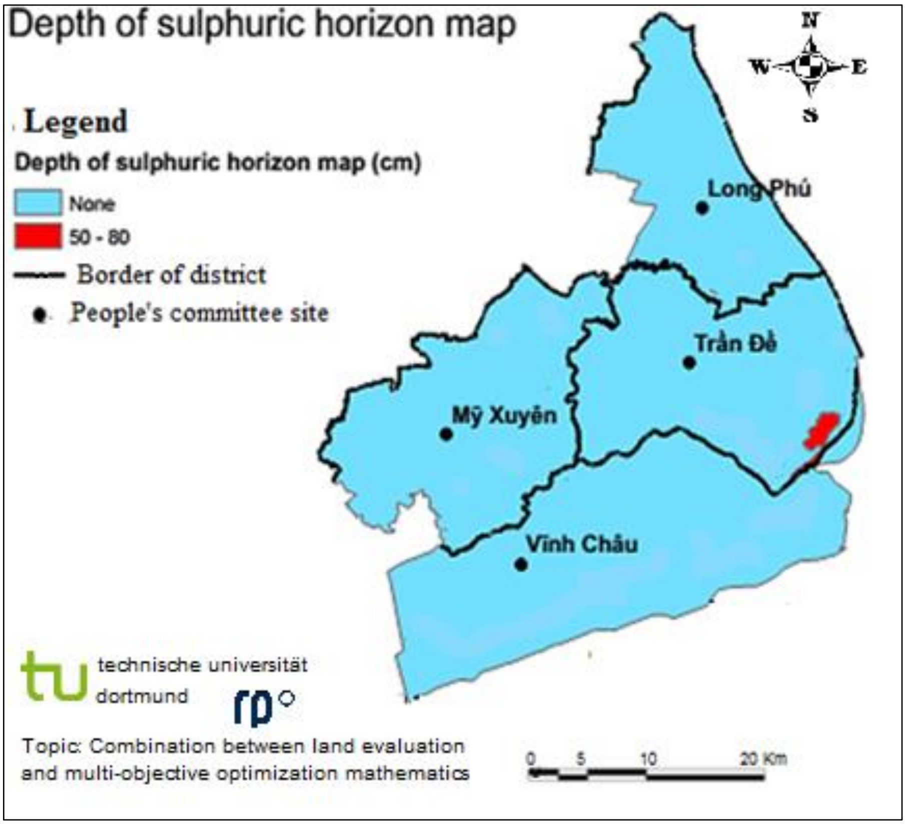


Figure 5.1.a. Land characteristic: Soil type



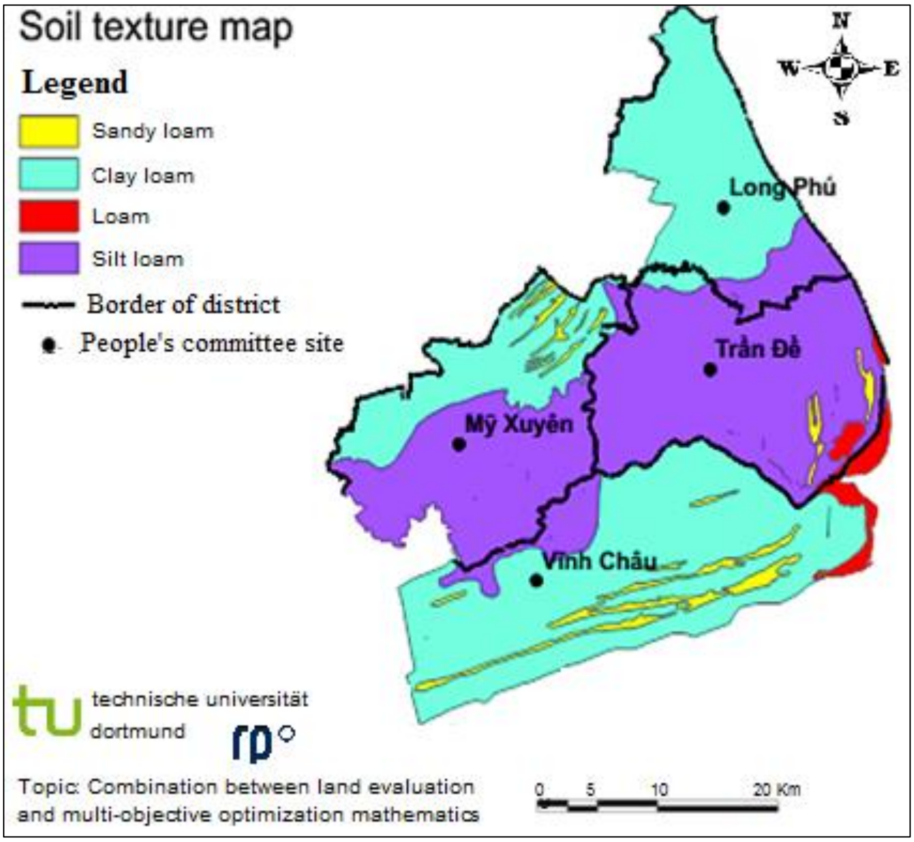
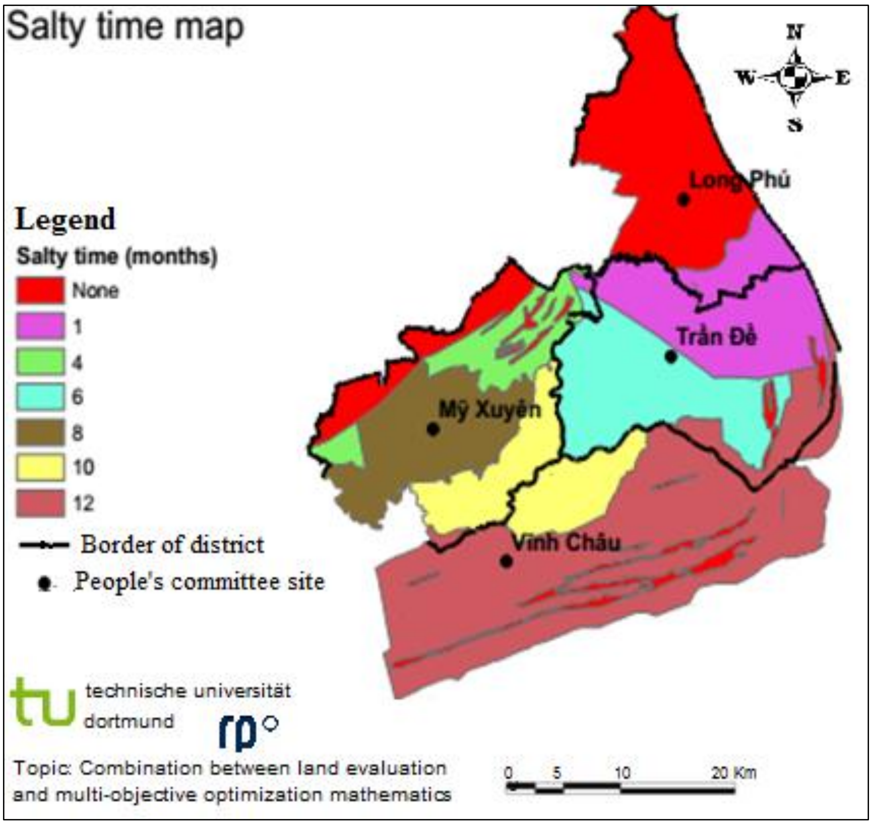


Figure 5.1.b. Land characteristics: Depth of sulphuric horizon and Soil texture



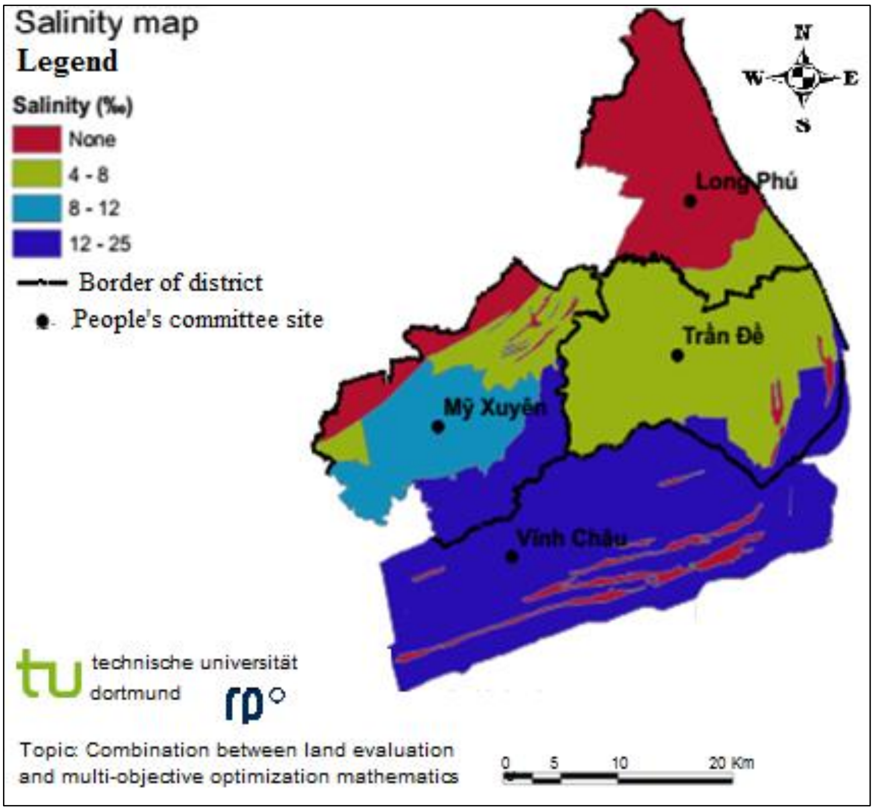
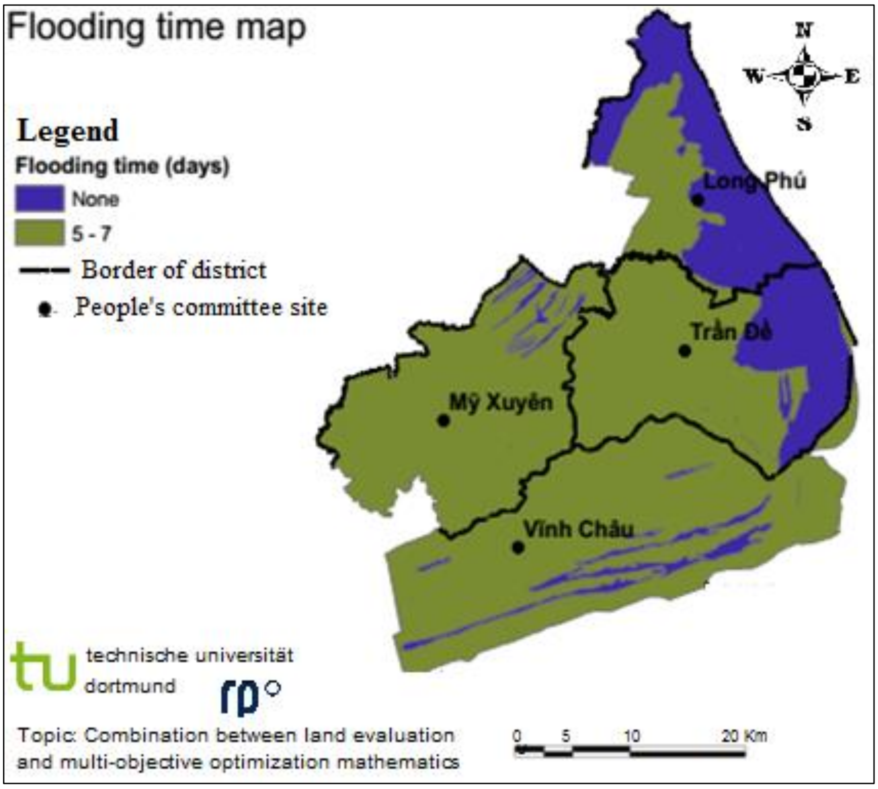


Figure 5.1.c. Land characteristics: Salty time and Salinity



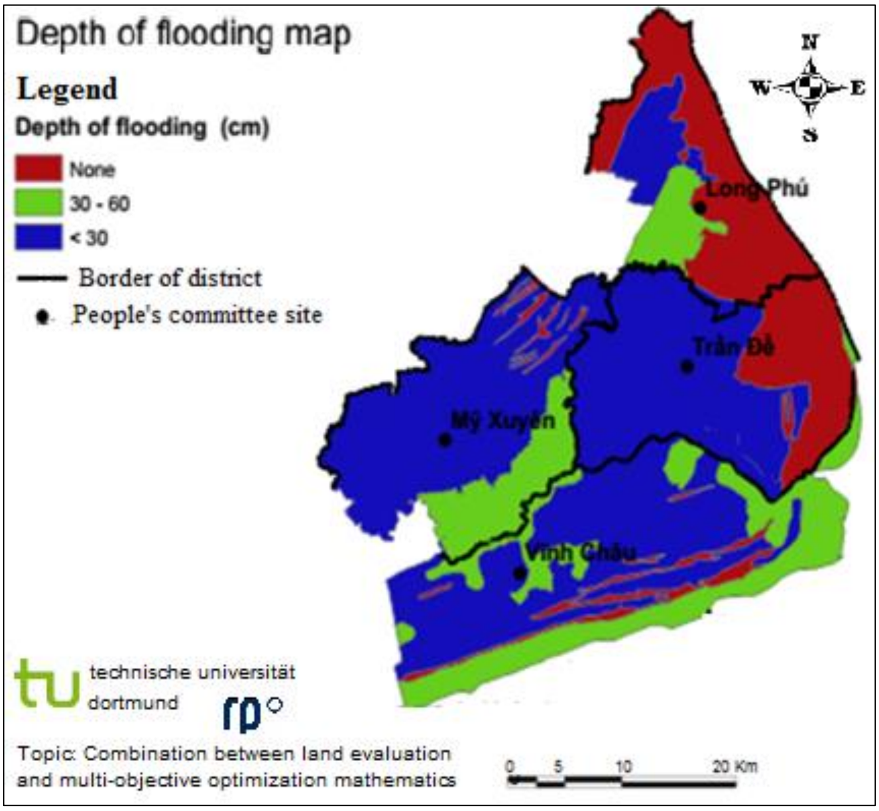


Figure 5.1.d. Land characteristics: Flooding time and Depth of flooding

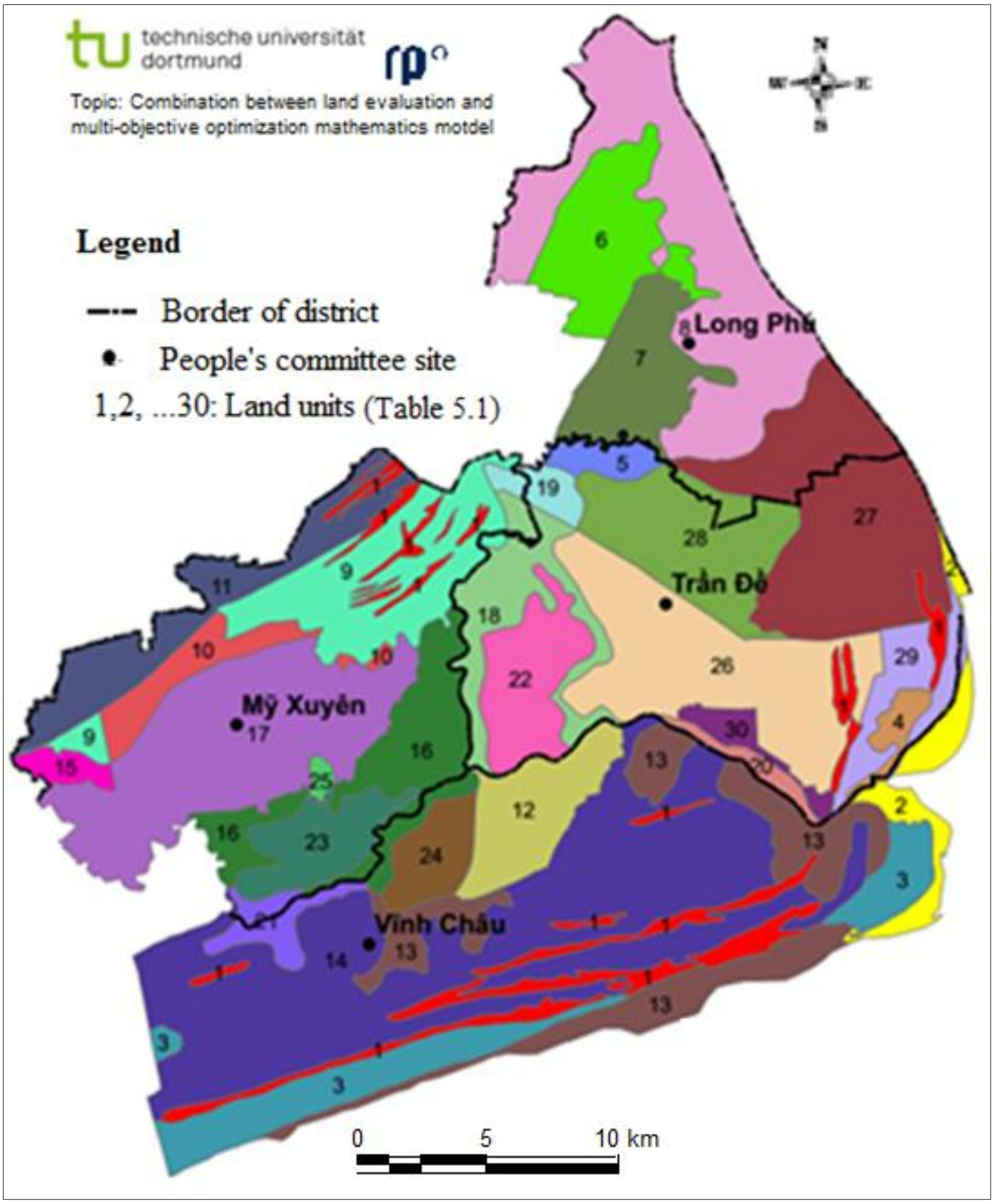


Figure 5.2. The land mapping units

Table 5.1. Characteristics and area of land mapping units

LU	Soil			Water				Area (ha)
	Soil type	Depth of sulphuric horizon (cm)	Soil texture	Salty time (month)	Salinity (‰)	Flooding time (days)	Depth of flooding (cm)	
1	ARd	None	Sandy loam	None	0	None	0	5,448.5
2	Fleus	None	Loam	12	12 - 25	5- 7	30–60	2,233.7
3	FLegs	None	Clay loam	12	12 - 25	5 – 7	30–60	5,451.3
4	FLt(oep-j)uhs	50-80	Loam	12	12 - 25	None	0	723.5
5	GLeu	None	Clay loam	1	4 - 8	5 – 7	< 30	890.4
6	GLeu	None	Clay loam	None	0	5 – 7	< 30	4,449.3
7	GLeu	None	Clay loam	None	0	5 – 7	30–60	8,196.6
8	Gleu	None	Clay loam	None	0	None	0	11,559.4
9	GLeuhs	None	Clay loam	4	4 - 8	5 – 7	< 30	6,310.2
10	GLeuhs	None	Clay loam	8	8 - 12	5 – 7	< 30	2,003.7
11	GLeuhs	None	Clay loam	None	0	5 – 7	< 30	10,879.7
12	GLeus	None	Clay loam	10	12 - 25	5 – 7	< 30	3,458.5
13	GLeus	None	Clay loam	12	12 - 25	5 – 7	30– 60	7,626.5
14	GLeus	None	Clay loam	12	12 - 25	5 – 7	< 30	21,837.2
15	GLmohs	None	Silt loam	4	4 - 8	5 – 7	< 30	675.3
16	GLmohs	None	Silt loam	10	12 - 25	5 – 7	30 -60	5,171.5

17	GLmohs	None	Silt loam	8	8 - 12	5 – 7	< 30	10,581.7
18	GLmohs	None	Silt loam	6	4 - 8	5 – 7	< 30	3,625.7
19	GLmohs	None	Silt loam	1	4 - 8	5 – 7	< 30	901.8
20	GLmohs	None	Silt loam	12	12 - 25	5 – 7	< 30	618
21	GLmohs	None	Silt loam	12	12 - 25	5 – 7	30– 60	1,276.5
22	Glplihs	None	Silt loam	6	4 - 8	5 – 7	< 30	3,387.3
23	GLumhs	None	Silt loam	10	12 - 25	5 – 7	30– 60	2,560.7
24	GLumhs	None	Silt loam	10	12 - 25	5 – 7	< 30	1,782.8
25	GLumhs	None	Silt loam	8	8 - 12	5 – 7	< 30	214.5
26	GLumhs	None	Silt loam	6	4 - 8	5 – 7	< 30	8,621.6
27	GLumhs	None	Silt loam	1	4 - 8	None	0	9,759.4
28	GLumhs	None	Silt loam	1	4 - 8	5 – 7	< 30	5,399.7
29	GLumhs	None	Silt loam	12	12 - 25	None	0	2,204.6
30	Glumhs	None	Silt loam	12	12 - 25	5 - 7	< 30	845.2
							Total	**148,696.1**

Depending on land characteristics which affect the growth of LUTs, it was defined as land requirements (Table 5.2). Shrimp-rice rotation crops (LUT 3) and Shrimp crop (LUT 4) relate to aquaculture (shrimp crop). Therefore, land requirement of LUT 3 and LUT 4 will be not affected flooding time and depth of flooding characteristics.

Table 5.2. Required land characteristics for LUTs

LUTs / Land characteristics	LUT1 (3 rice)	LUT2 (2 rice)	LUT3 (Shrimp-Rice)	LUT4 (Shrimp)	LUT5 (Rice-Upland)
Soil texture	X	X	X	X	X
Soil type	X	X	X	X	X
Depth of sulphuric horizon	X	X	X	X	X
Flooding time	X	X	-	-	X
Depth of flooding	X	X	-	-	X
Salty time	X	X	X	X	X
Salinity	X	X	X	X	X

Note: X: Required,

-: Not required

Land suitability classification:

Factor rating of each land use type is based on the method of FAO (1976) which is classified into four levels (S1, S2, S3, N). Each LUT will be rated on how it scores X_i ($X_i \in [0, 10]$) and given weights w (w $\in$ [0, 1]) with each land characteristic. According to the group and individual interviews, the weight and scoring scale of each characteristic are defined in the study area. The results are presented in Table 5.3.

Table 5.3: Indicators and weights for scoring scale and values

Land Charac-terictics (LC) and Weight (w)	Land suitability classification in scoring scale (FAO) and Scoring value (Xi)										
	Level of LC	LUT 1		LUT 2		LUT 3		LUT 4		LUT 5	
		FAO	Xi	FAO	Xi	FAO	Xi	FAO	Xi	FAO	Xi
Soil texture w= 1/7	Sandy loam	S3	3	S3	3	N	0	N	0	S1	8.5
	Loam	S2	6	S2	6	S2	6	S2	6	S2	6
	Silt loam	S1	8	S1	8	S1	8	S1	8	S2	8
	Clay loam	S1	8	S1	8	S1	8	S1	8	S2	8
Soil type w= 1/7	GLeu	S1	8.5	S1	8.5	S3	2	N	0	S1	8.5
	GLeuhs	S2	5	S2	5	S2	7	S2	6	S2	5
	GLumhs	S2	5	S2	5	S1	8	S2	6	S2	5
	GLmohs	S2	5	S2	5	S1	8	S2	6	S2	5
	GLplihs	S2	5	S2	5	S2	7	S2	6	S2	5
	GLeus	S3	3	S3	3	S3	2	S1	8	S3	3
	FLt	S3	2	S3	2	S3	2	S3	2	S3	2
	ARd	N	0	N	0	N	0	N	0	S3	2
	FLeus	N	0	N	0	N	0	S1	8.5	N	0
	FLegs	N	0	N	0	N	0	S1	8.5	N	0
Depth of sulphuric horizon (cm) w= 1/7	None	S1	8.5	S1	8.5	S1	8	S1	8	S1	8
	50-80	S2	6	S2	6	S2	5	S2	5	S2	6
Flooding time (day) w= 1/7	None	S1	8	S1	8	-	-	-	-	S1	8
	5-7	S2	7	S2	7	-	-	-	-	S3	6
Depth of flooding (cm) w= 1/7	None	S1	8.5	S1	8.5	-	-	-	-	S1	8.5
	<30	S1	8	S1	8	-	-	-	-	S1	8
	30-60	S2	6	S2	6	-	-	-	-	S2	5
Salinity (‰) w= 1/7	None	S1	8	S1	8	N	0	N	0	S1	8
	4-8	N	0	N	0	S2	6	S3	2	S3	2
	8-12	N	0	N	0	S2	7	S2	7	N	0
	12-25	N	0	N	0	S1	8	S1	8	N	0
	None	S1	8	S1	8	N	0	N	0	S1	8.5

Salty time (month) **w= 1/7**	1	N	0	N	0	N	0	S3	2	S1	8
	4	N	0	N	0	S1	8	S3	2	S3	2
	6	N	0	N	0	S1	8	S3	3	N	0
	8	N	0	N	0	S1	8	S1	8	N	0
	10	N	0	N	0	S3	3	S1	8.5	N	0
	12	N	0	N	0	S3	3	S1	8.5	N	0

Matching to present land suitability classification by S1, S2, S3, N:

It is based on the principle of maximizing limit factors (FAO, 1976) for LMUs.

Land suitability zoning:

By classification, land suitability on LMUs is conducted. After that, the establishment of a similar level of adaptation is formed into zones.

5.2. Land suitability in the crisp environment

5.2.1. Land physical suitability by FAO method

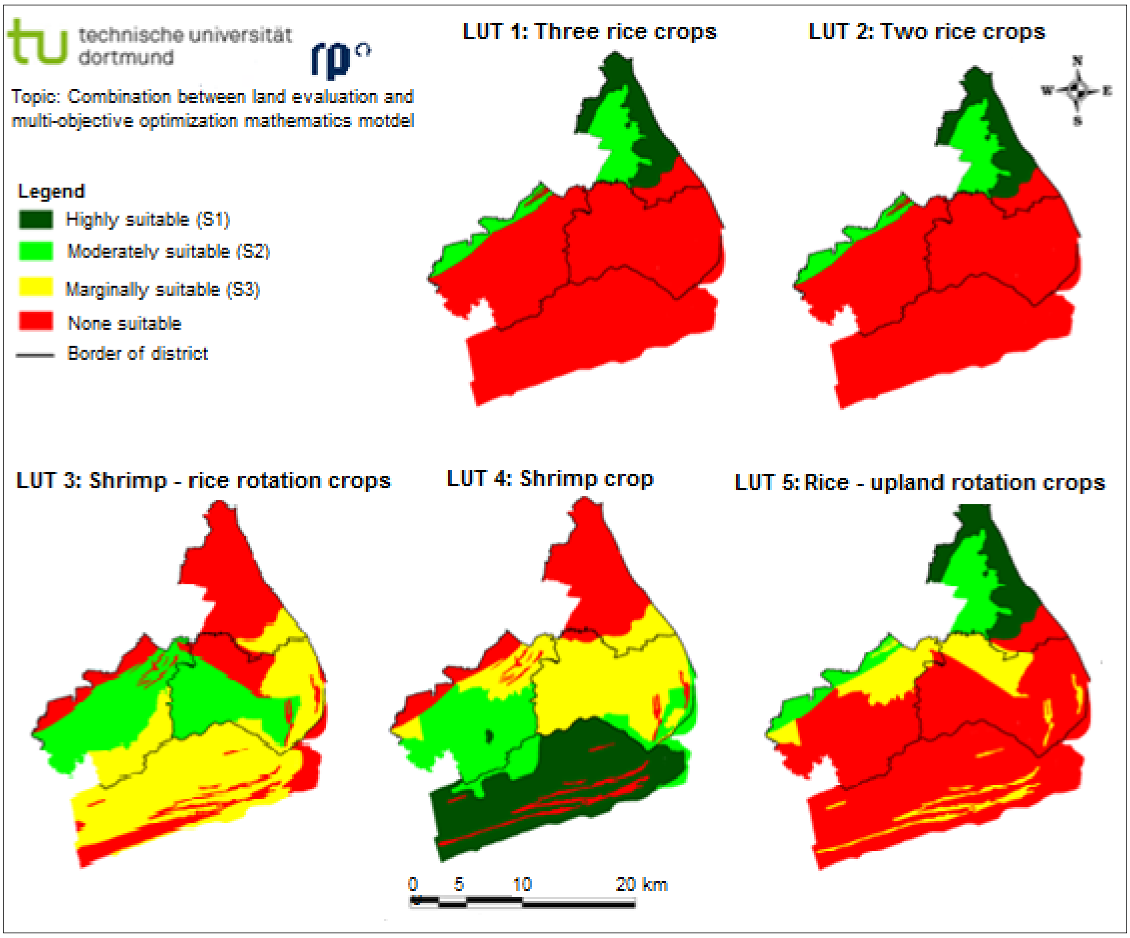


Figure 5.3. Map of land physical suitability (FAO) in the crisp environment

5.2.2. Land physical suitability by MCE (Multi Criteria Evaluation)

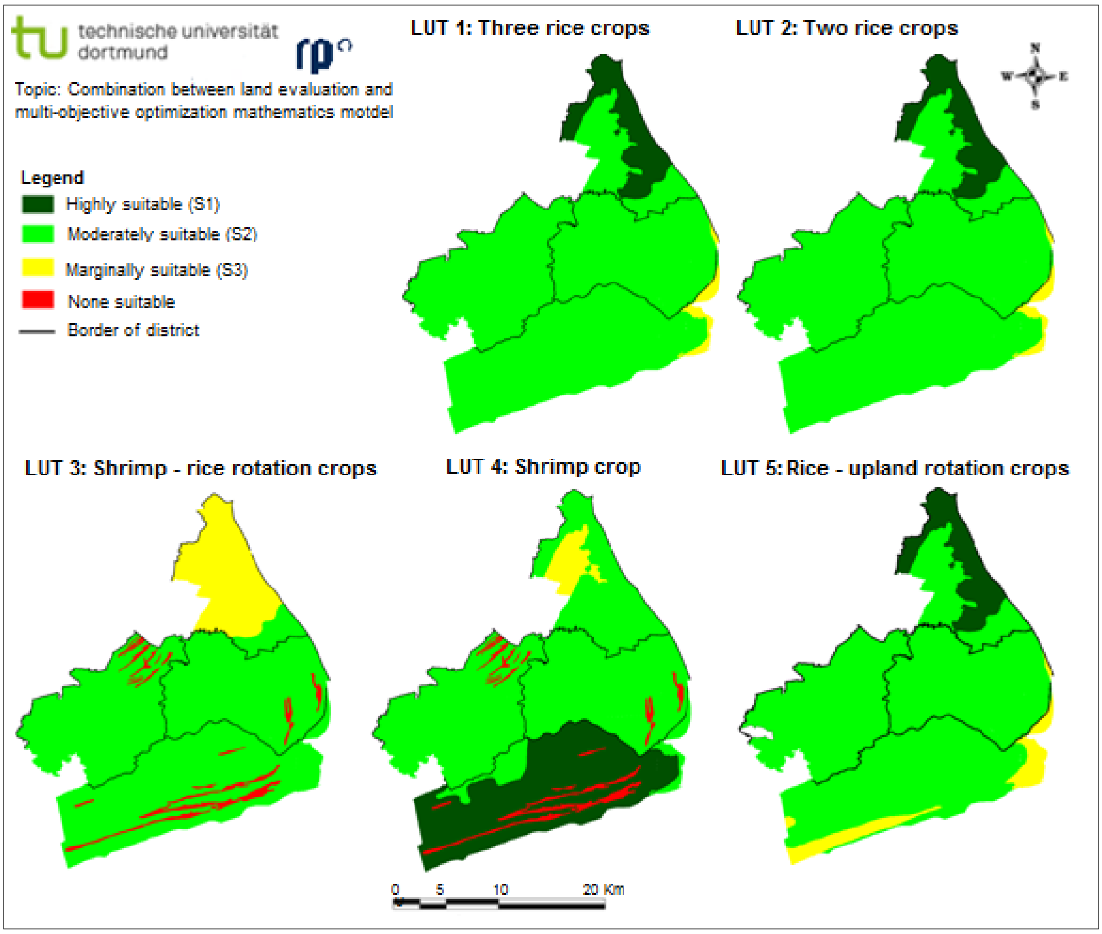


Figure 5.4. Map of Land physical suitability (MCE) in the crisp environment

5.3. Land suitability in fuzzy environment

5.3.1. Land physical suitability by fuzzy operator Max

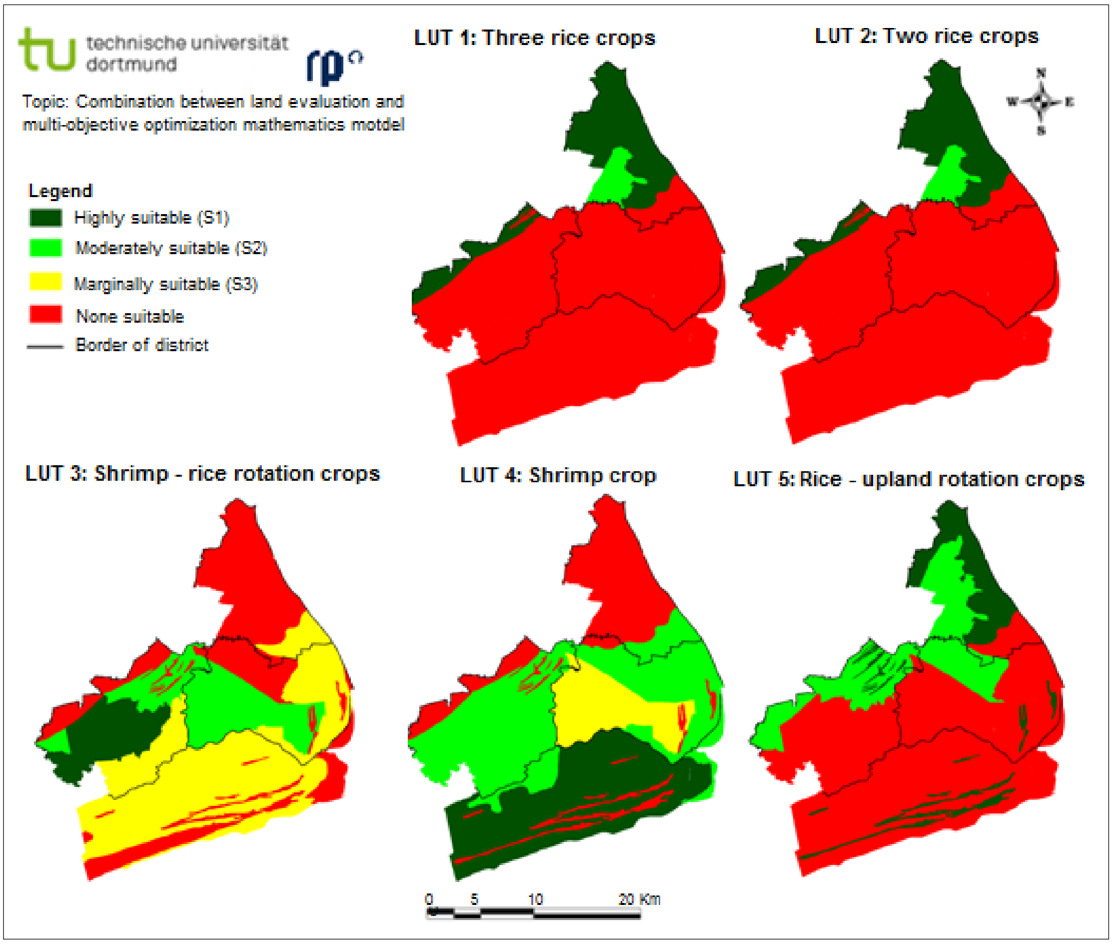


Figure 5.5. Map of land physical suitability (MAX) in fuzzy environment

5.3.2. Land physical suitability by fuzzy operator LUKASIEWICZ

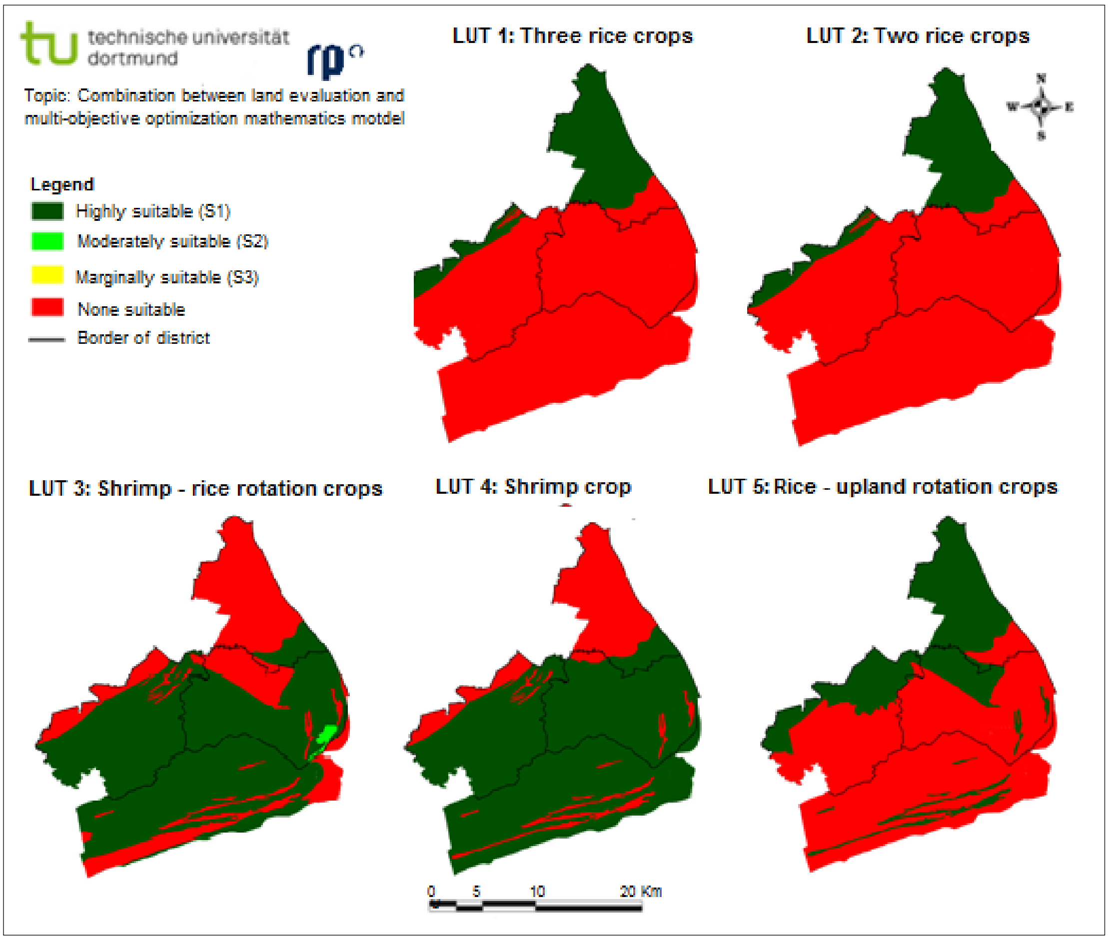


Figure 5.6. Map of land physical suitability (LUKASIEWICZ) in fuzzy environment

5.4. Comparison between crisp environment and fuzzy environment in the land physical analysis

Comparing the area of suitability classification between crisp environment (FAO, MCE) and fuzzy environment (MAX, LUKASIEWICZ), the highly suitable class (S1) in the fuzzy environment is larger than in the crisp environment, except for LUT 4, where it is equal in three methods (FAO, MCE, MAX). A part of this area converses to the classes moderately suitable (S2) and marginally suitable (S3). Regarding the area of the none-suitable class (N), it is equal in the three methods FAO, MAX, LUKASIEWICZ, and converses to S2 and S3 in the MCE method. Therefore, the MCE method leads to an unreliable result for land suitability (Figure 5.7).

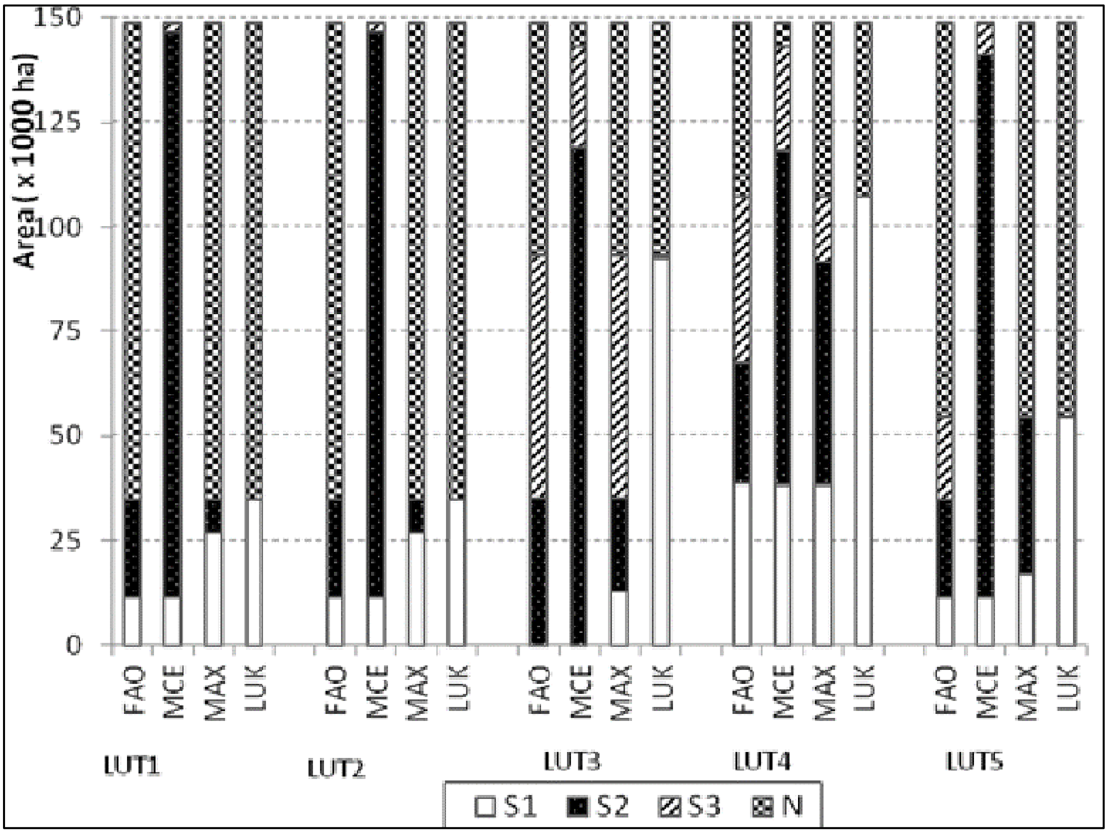


Figure 5.7. The area of land physical suitability by 4 methods (FAO, MCE, MAX, LUKASIEWICZ)

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp - rice rotation crops, LUT 4: Shrimp crop, LUT 5: Rice - upland rotation crops.

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable.

The maximum limited factor method in land physical suitability (FAO, 1976) is not a flexible rule because the worst land characteristic will decide the final suitable class. The MCE method is very general because of the average of all factors in the crisp environment and it does not have the priority. In contrast, MAX method is a priority for some good factors. Especially, the LUKASIEWICZ method is strongly efficient because it is interactive with all factors together in the fuzzy environment. This is a useful method which applies in the sustainable land evaluation.

5.5. Economic land suitability in Fuzzy operator by LUKASIEWICZ

Economic land suitability is a method for predicting the micro-economic value of implementing a given land-use system on a given land area. This is a more useful prediction of land performance than a purely physical evaluation since many land-use decisions are made by economic value (Rossiter, 1995). However, this method is the only evaluation for every economic indicator. This means that economic land suitability in the Fuzzy environment by LUKASIEWICZ operator is necessary.

Economic land evaluation is calculated based on four indicators: income, cost, benefit, and benefit per cost ratio (B/C). For the determination of land classes in land economic suitability, pattern introduced by FAO is used (1976) as mentioned below:

Economic indicators having > 80%$(\frac{\sum_{i=1}^{5} LUT_i}{5})$ are in S_1 class

Economic indicators having from 40%$(\frac{\sum_{i=1}^{5} LUT_i}{5})$ to 80%$(\frac{\sum_{i=1}^{5} LUT_i}{5})$ are in S_2 class

Economic indicators having from 20%$(\frac{\sum_{i=1}^{5} LUT_i}{5})$ to < 40%$(\frac{\sum_{i=1}^{5} LUT_i}{5})$ are in S_3 class

Economic indicators having < 20%$(\frac{\sum_{i=1}^{5} LUT_i}{5})$ are in N class

Classify four economic indicators of LUTs such as: Income (Million VND/ha/year), Cost (Million VND/ha/year), Benefit (Million VND/ha/year), Benefit per Cost- B/C. The membership degrees are conversed by fuzzification via membership function µ(x) for four fuzzy sets of 4 levels of suitability (S_1: Highly suitable, S_2: Moderately suitable, S_3: Marginally suitable, N: None suitable) (Figure 5.8).

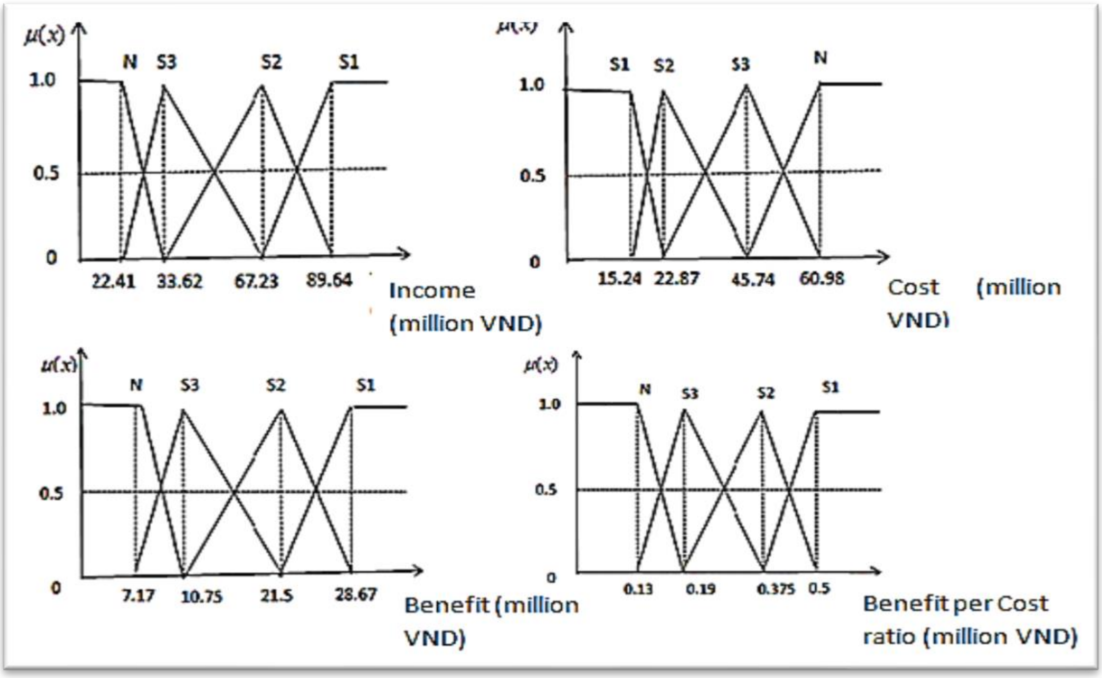


Figure 5.8. Fuzzification via membership functions for 4 linguistic terms of suitability level of Income, Cost, Benefit, and Benefit per Cost

Hierarchical structure and weights of the economic indicator are identified by the PRA method (Table 5.4).

Table 5.4. Hierarchical structure and weights of economy indicator

Level 1 (Weight)	**Level 2 (Weight)**
Economy	Income (0.23)
	Cost (0.20)
	Benefit (0.30)
	Benefit per cost ratio- B/C (0.27)

Economic suitability evaluation is carried only on those areas which are physically suitable. If a land unit shows a degree of unsuitability in the physical suitability assessment, they are not used in the further suitability assessment. The none-suitable class (N) of the result of land physical suitability is not considered and assigned as non-suitable for both economic and physical matters (FAO, 1976). The result showed land economic suitability by Lukasiewicz operator (Figure 5.9).

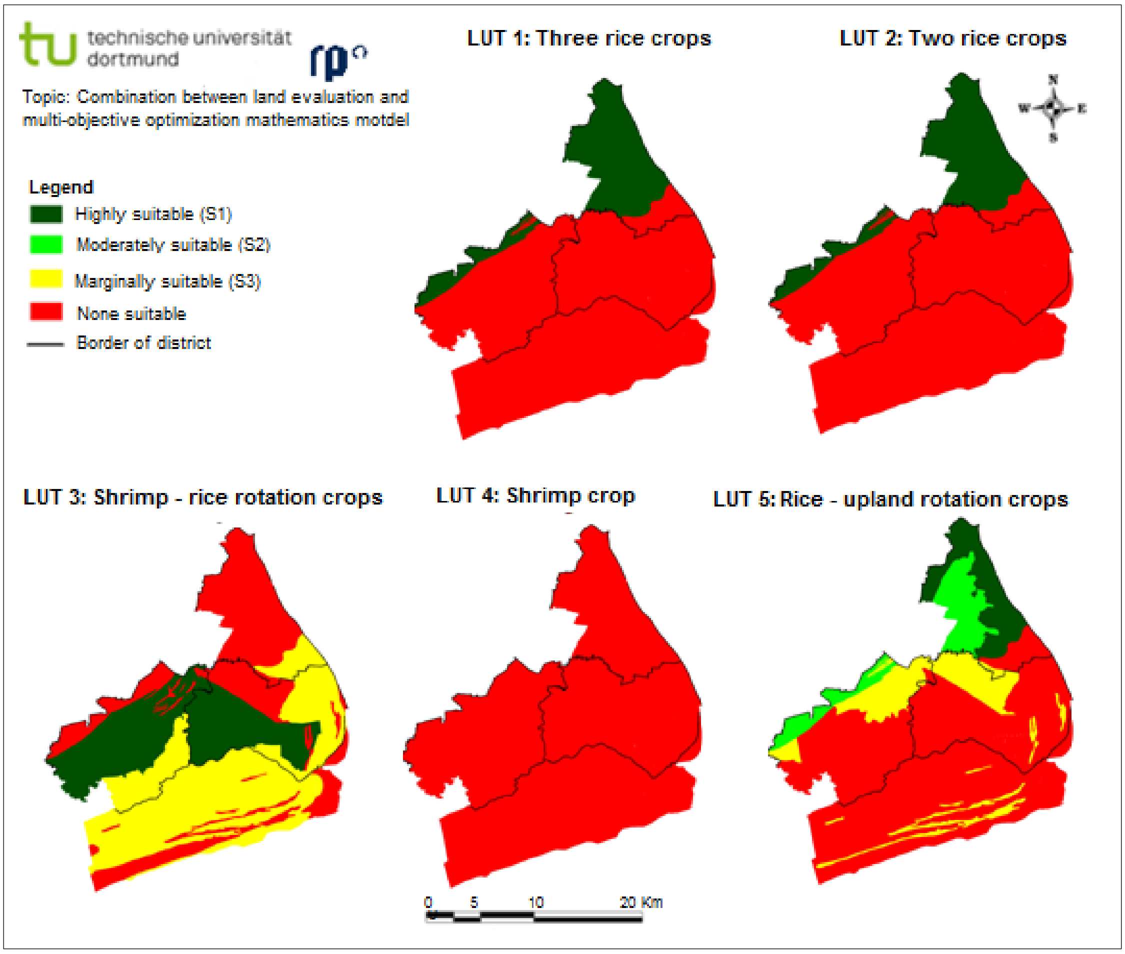


Figure 5.9. Map of land economic suitability in Fuzzy operator by Lukasiewicz

5.6. Land sustainable suitability in Fuzzy operator by LUKASIEWICZ

According to the framework of evaluating sustainable land by FAO (1993, 2007), natural, economic and social conditions in the study area, consultation of farmers by the PRA (Participatory Rural Appraisal) method and ideas of experts in related fields were used to identify sustainability indicators and their respective weights (Table 5.5). The sustainable indicators will be rated on how it scores with each sustainability indicator. The scoring scales and values along each indicator are defined through interviewing the experts and experienced farmers in the study area.

Table 5.5. AHP and weights of indicators

Level 1 (Weight)	**Level 2 (Weight)**	**Level 3 (Weight)**
Economy (0.4)		Income (0.23)
		Cost (0.2)
		Benefit (0.3)
		Benefit per cost ratio- B/C (0.27)
Society (0.2)		Available labor capacity (0.09)
		Farming habits (0.32)
		Government policy (0.27)
		Technical support (0.20)
		Cultural habits (0.05)
		Creating jobs capacity (0.07)
Natural resources and environment (0.4)	Physic (0.5)	Soil texture (0.143) Soil type (0.143) Depth of sulphuric horizon (0.143) Flooding time (0.143) Salty time (0.143) Depth of flooding (0.143) Salinity (0.143)
	Environment (0.5)	Biodiversity capacity (0.27)
		Herbicide and pesticide amount (0.3)
		Salinization in soil (0.23)
		Acidification in soil (0.2)

The result showed sustainable land suitability in the Fuzzy operator by Lukasiewicz with 11 suitable zones (Figure 5.10).

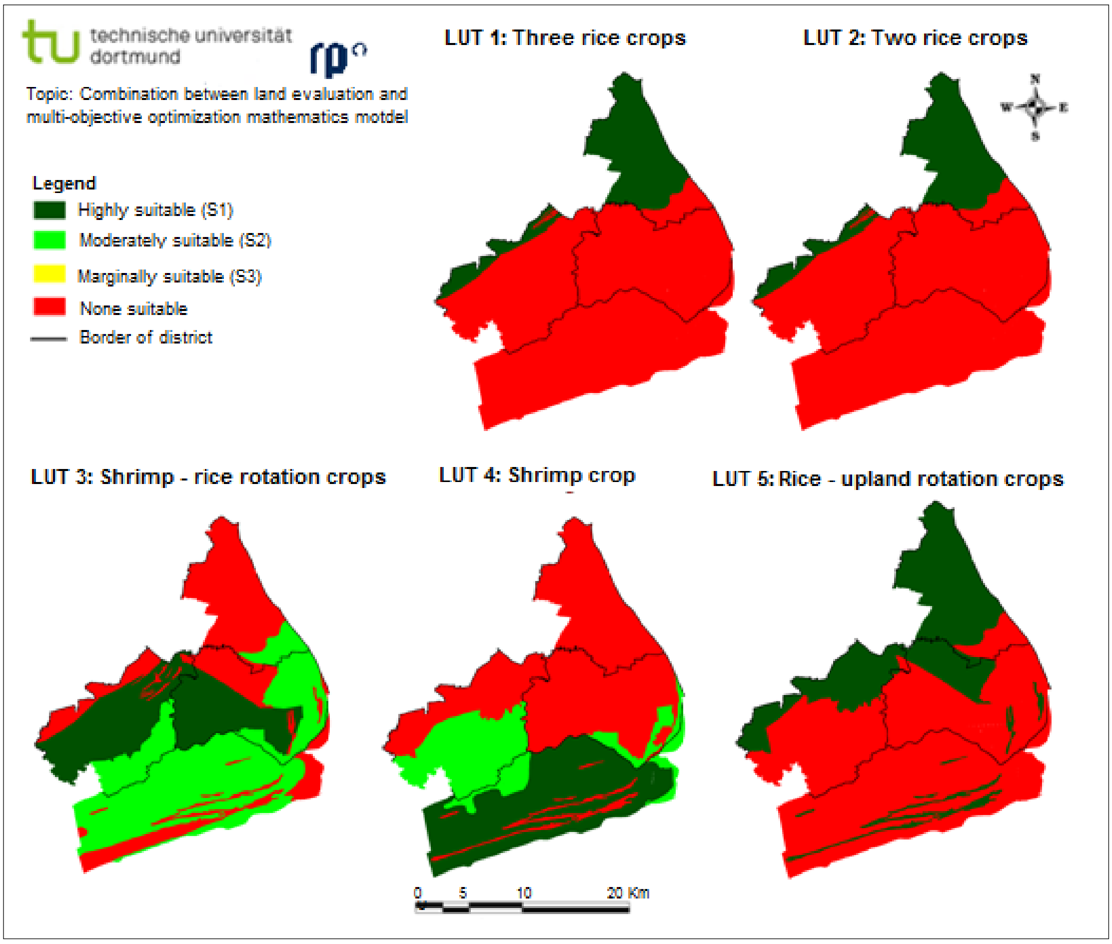


Figure 5.10. Map of land sustainable suitability in Fuzzy operator by Lukasiewicz

5.7. Comparison of land physical, economic and sustainable suitability

The bar graph (Figure 5.11) illustrates that the proportion of the highly suitable class (S1) of sustainable land suitability is almost less than the ones of land physical and land economic suitability. It proves that evaluating for sustainable land suitability is needed considering multi-aspects as the economy, society, natural resources and environment because the evaluation is separate which has more risks for land use and land management. Although having high proportions in terms of physical suitability, it can be not suitable or declines significantly on economic suitability such as the shrimp- rice rotation crops (LUT 3), shrimp crops (LUT 4) and rice- upland rotation crops (LUT 5). The market for agricultural products plays a vital role in sustainable land management.

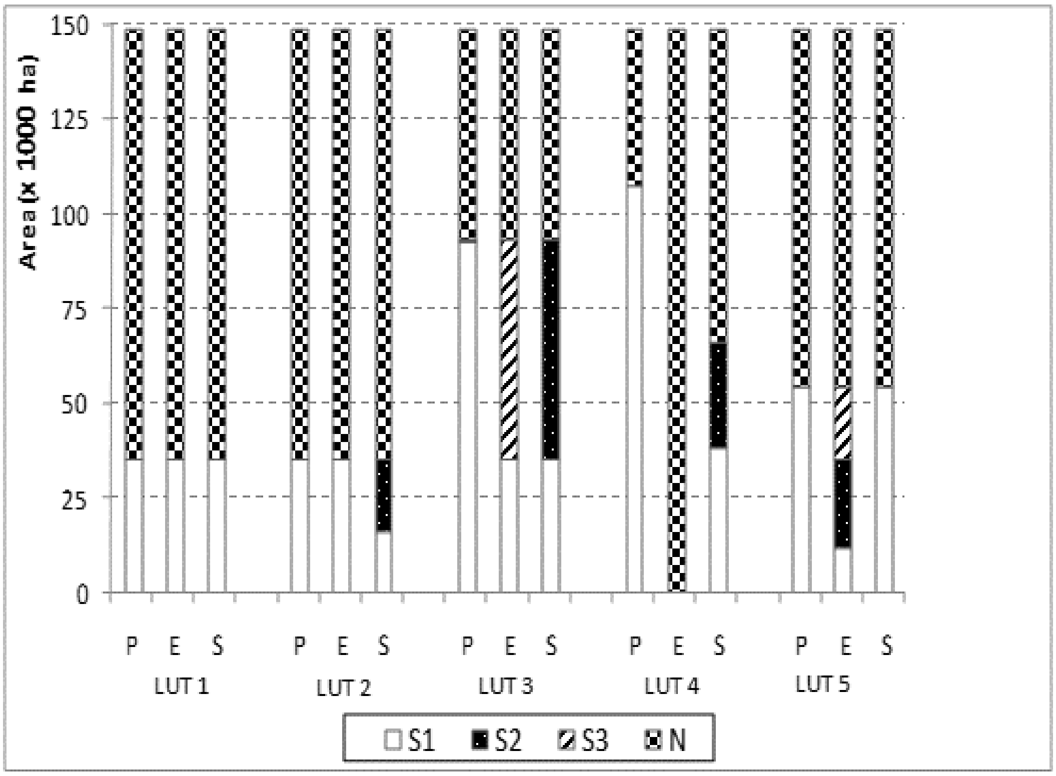


Figure 5.11. To compare land physical, economic and sustainable suitability

P: Land physical suitability; E: Land economic suitability, S: Land sustainable suitability

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp- Rice rotation crops, LUT 4: Shrimp crop,

LUT 5: Rice- Upland rotation crops

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable

5.8. Fuzzy multi-objective linear programming (FMOLP)

5.8.1. The objective linear programming function

Land evaluation is an essential tool to compare or match land use requirements with characteristics of different tracts of land in land use planning. Therefore, the variables of FMOLP are based on the land physical suitability (Figure 5.12)

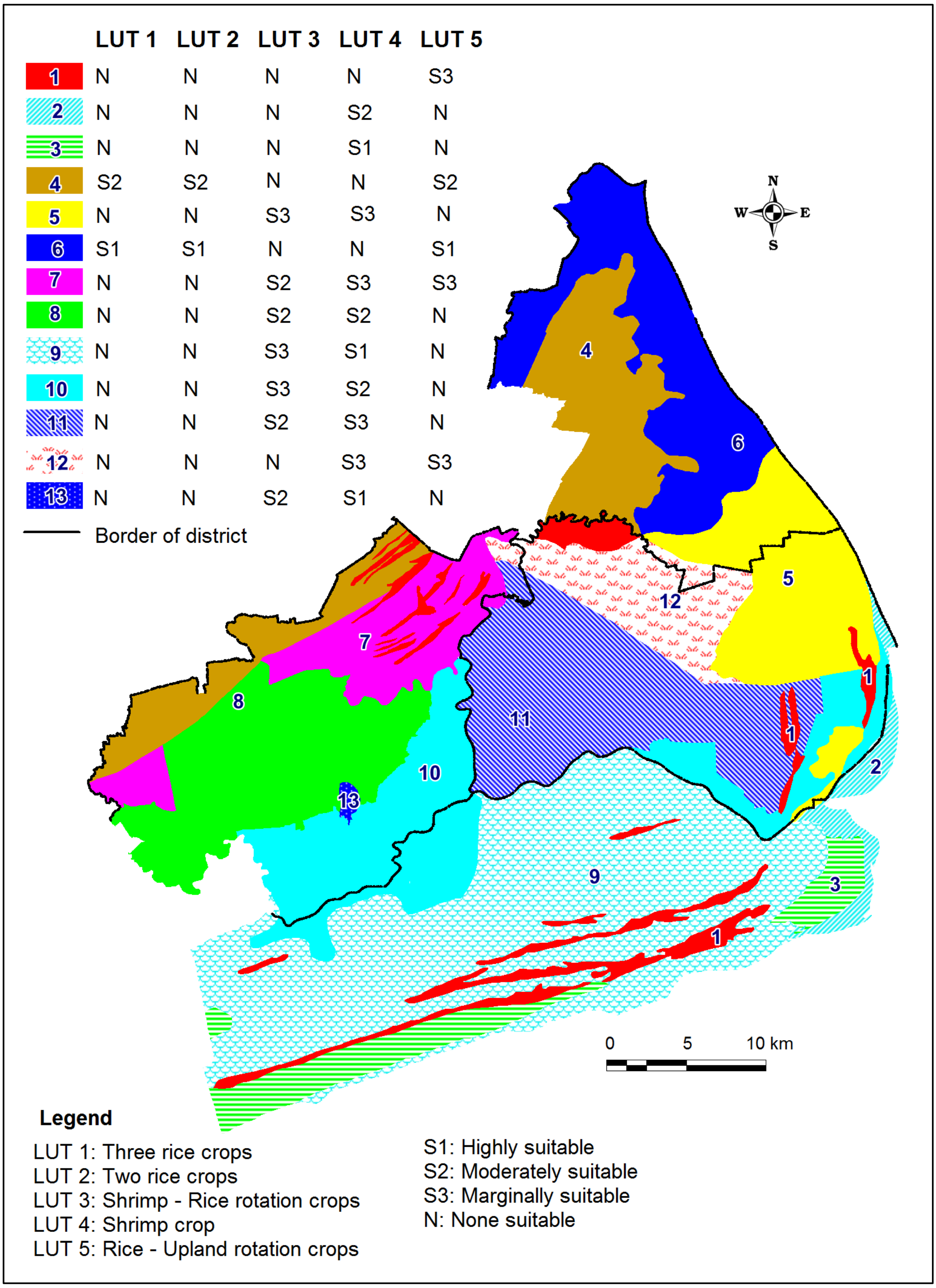


Figure 5.12. The regions of land physical suitability

X_{ijk} : Agricultural land use type- LUT (ha), $X_{ijk} \geq 0$

i (i = 1, 2, 3, 4, 5): the number of LUT1, LUT2, LUT3, LUT4, LUT5.

j: Suitability levels S1, S2, S3 (j = 1,2,3) from result of land physical suitability

k: The number of suitability region 1, 2,…,13 (k = 1,2,..,13).

There are 26 variables: X_{116}, X_{124}, X_{216}, X_{224}, X_{327}, X_{328}, X_{3211}, X_{3213}, X_{335}, X_{339}, X_{3310}, X_{413}, X_{419}, X_{4113}, X_{422}, X_{428}, X_{4210}, X_{435}, X_{437}, X_{4311}, X_{4312}, X_{516}, X_{524}, X_{531}, X_{537}, X_{5312}.

Land use allocation towards sustainable development involves a set of sustainability objectives related to economy, society, and environment. So, this study establishes five objectives as linear programming objective functions for the FMOLP model.

The linear programming objective function

The maximize Income function: Z_1 (Million VND/ha/year)

$$Z_1 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(1)} X_{ijk} \rightarrow Max \tag{5.1}$$

The maximize Benefit per cost ratio (B/C) function: Z_2

$$Z_2 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(2)} X_{ijk} \rightarrow Max \tag{5.2}$$

The maximize Employment function: Z_3 (day)

$$Z_3 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(3)} X_{ijk} \rightarrow Max \tag{5.3}$$

The maximize highly suitable area of land physical suitability: Z_4 (ha)

$$Z_4 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(4)} X_{ijk} \rightarrow Max \tag{5.4}$$

The maximize protect environment : Z_5

$$Z_5 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(5)} X_{ijk} \rightarrow Max \tag{5.5}$$

$b_{ijk(l)}$: coefficients of the objective function, (l =1,2,3,4,5).

$b_{ijk(5):}$ fuzzy environmental protection coefficient.

The constraint functions

The constraint of land suitability area (C_1) (ha)

$$\sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} X_{ijk} \leq S_k \qquad (5.6)$$

S_k: Land physical suitability area (ha)

The constraint of the agricultural land area (C_2) (ha)

According to the master plan of four districts in 2020, the total agricultural land is 118,297.07 ha (The Government, 2013).

$$\sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} X_{ijk} \leq 118.297{,}07 \qquad (5.7)$$

The constraint of the available agricultural labor force (C_3) (labor day)

The forecasting population of four districts in 2020 is 1,339,142, in which the persons of working age amount to 893,877. The agricultural labor proportion is 50.75%, with 453,643 people (General Statistics Office, 2014). According to the result of interviews of the research, one agricultural labor person worked 233 days/year. Therefore, the total of available agricultural labor days is 105,698,721.

$$\sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk} X_{ijk} \leq 105.698.721 \qquad (5.8)$$

$b_{ijk:}$ The number of labor days of LUT_i/ ha/ year (labor day)

The constraint of cost (C_4) (Million VND/year)

The optimal objective is to establish a proper methodology to identify the best land use, based on the natural conditions, so that land treatment investments can be at the minimum level (Lilian et al. 2015). According to the result of the interview, the cost for all LUTs does not exceed the farmer`s investment capacity 11,333,621 (Million VND/year).

$$\sum_{i=1}^{5}\ \sum_{j=1}^{3}\ \sum_{k=1}^{13} C_{ijk}X_{ijk} \le 11{,}333{,}621 \qquad (5.9)$$

C_{ijk}: The cost of LUTs ((Million VND/year).

5.8.2. The fuzzy linear membership function

The result showed that linear programming for optimal five objectives Z_1, Z_2, Z_3, Z_4, Z_5 (Table 5.6).

Table 5.6. Pay- Off table

	Z1	Z2	Z3	Z4	Z5
Z1	9,660,436	30,770	15,856,122	49,933	7,788,906
Z2	7,694,748	54,802	15,590,394	11,559	8,998,089
Z3	8,297,448	33,185	17,656,236	13,964	9,714,151
Z4	3,557,445	9,633	5,852,156	50,148	2,062,084
Z5	8,433,069	34,653	17,647,199	9,669	9,914,002

Establish fuzzy linear membership functions

$$\mu(Z_1) = \frac{Z_1 - Z_1^{W}}{Z_1^{B} - Z_1^{W}} = \frac{Z_1 - 3{,}557{,}445}{9{,}660{,}436 - 3{,}557{,}445} = \frac{Z_1}{6{,}102{,}991} - 0.58 \qquad (5.10)$$

$$\mu(Z_2) = \frac{Z_2 - Z_2^{W}}{Z_2^{B} - Z_2^{W}} = \frac{Z_{21} - 9{,}633}{54{,}802 - 9{,}663} = \frac{Z_2}{45{,}169} - 0.21 \qquad (5.11)$$

$$\mu(Z_3) = \frac{Z_3 - Z_3^{W}}{Z_3^{B} - Z_3^{W}} = \frac{Z3 - 5{,}852{,},156}{17{,}656{,}236 - 5{,}852{,}156} = \frac{Z_3}{11{,}804{,}080} - 0.5 \qquad (5.12)$$

$$\mu(Z_4) = \frac{Z_4 - Z_4^{W}}{Z_4^{B} - Z_4^{W}} = \frac{Z_4 - 9{,}669}{50{,}148 - 9{,}669} = \frac{Z_4}{40{,}479} - 0.24 \qquad (5.13)$$

$$\mu(Z_5) = \frac{Z_5 - Z_5^{w}}{Z_5^{B} - Z_5^{w}} = \frac{Z_5 - 2{,}062{,}084}{9{,}914{,}002 - 2{,}062{,}084} = \frac{Z_5}{7{,}851{,}918} - 0.26 \qquad (5.14)$$

Fuzzy multi-objective function u:

$$u = w_1\left(\frac{Z_1}{6{,}102{,}991} - 0.58\right) + w_2\left(\frac{Z_2}{45{,}169} - 0.21\right) + w_3\left(\frac{Z_3}{11{,}804{,}080} - 0.5\right) + w_4\left(\frac{Z_4}{40{,}479} - 0.24\right) + w_5\left(\frac{Z_5}{7{,}851{,}918} - 0.26\right) \qquad (5.15)$$

5.9. Incorporation of decision makers

5.9.1. Weight of compromise

To look for weights for a set of activities according to importance, is a fundamental problem of decision theory. Importance is usually judged according to several criteria. Each criterion may be shared by some or by all of the activities (Saaty, 1977). According to Kok, Verburg, & Veldkamp (2007), a valuable method to identify and explore possible futures are scenarios. Scenario development is a relatively new and thus under-explored method in land use change research, certainly compared to modelling.

DMs with a satisfactory degree of the preferences propose alternative solutions for better land use planning by incorporating the preferences of DMs using a compromise index to identify weights (w) for five objectives by eights Scenarios (Table 5.7).

Table 5.7. Scenarios of FMOLP by incorporation of the preferences of decision makers

Scenario	Linear programming functions (Z)					Constraints (C)			
	Z_1 Income	**Z_2** B/C	**Z_3** Employment	**Z_4** Land	**Z_5** Environment	C_1	C_2	C_3	C_4
1	Economy > Society > Environment: Z1 > Z2 > Z3 > Z5 > Z4					☑	☑	☑	☑
2	Economy > Environment > Society: Z1 > Z2 > Z5 > Z4 > Z3					☑	☑	☑	☑
3	Economy = Society = Environment : Z1 = Z2 = Z3 = Z4 = Z5					☑	☑	☑	☑
4	☑					☑	☑	☑	☑
5		☑				☑	☑	☑	☑
6			☑			☑	☑	☑	☑
7				☑		☑	☑	☑	☑
8					☑	☑	☑	☑	☑

Scenario 1: More priority for economic and social development

Economy > Society > Environment: $Z_1 > Z_2 > Z_3 > Z_5 > Z_4$

The Crisp Pair-wise Comparison among objectives of Expert 1

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 2 & 2 & 9 & 5 \\ 1/2 & 1 & 1/2 & 2 & 3 \\ 1/2 & 2 & 1 & 5 & 7 \\ 1/9 & 1/2 & 1/5 & 1 & 1 \\ 1/5 & 1/3 & 1/7 & 1 & 1 \end{bmatrix} \end{array}$$

CR = 0.02

The Crisp Pair-wise Comparison among objectives of Expert 2

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 5 & 1 & 9 & 7 \\ 1/5 & 1 & 1/3 & 2 & 4 \\ 1 & 3 & 1 & 5 & 7 \\ 1/9 & 1/2 & 1/5 & 1 & 1/2 \\ 1/7 & 1/4 & 1/7 & 2 & 1 \end{bmatrix} \end{array}$$

CR = 0.04

The Crisp Pair-wise Comparison among objectives of Expert 3

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 5 & 3 & 5 & 8 \\ 1/5 & 1 & 1 & 3 & 3 \\ 1/3 & 1 & 1 & 3 & 4 \\ 1/5 & 5 & 1/3 & 1 & 1 \\ 1/8 & 1/3 & 1/4 & 1 & 1 \end{bmatrix} \end{array}$$

CR = 0.02

The Crisp Pair-wise Comparison among objectives of Expert 4

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 4 & 1 & 6 & 5 \\ 1/4 & 1 & 1/3 & 3 & 4 \\ 1 & 3 & 1 & 9 & 9 \\ 1/6 & 1/3 & 1/9 & 1 & 1/2 \\ 1/5 & 1/4 & 1/9 & 2 & 1 \end{bmatrix} \end{array}$$

CR = 0.03

The Crisp Pair-wise Comparison among objectives of Expert 5

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 3 & 1 & 4 & 2 \\ 1/33 & 1 & 1/5 & 2 & 1 \\ 1 & 5 & 1 & 3 & 3 \\ 1/4 & 1/2 & 1/3 & 1 & 1/2 \\ 1/2 & 1 & 1/3 & 2 & 1 \end{bmatrix} \end{array}$$

CR = 0.02

The Crisp Pair-wise Comparison among objectives of Expert 6

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 3 & 1 & 7 & 7 \\ 1/3 & 1 & 1/3 & 3 & 2 \\ 1 & 3 & 1 & 9 & 3 \\ 1/7 & 1/3 & 1/9 & 1 & 1/3 \\ 1/7 & 1/2 & 1/3 & 3 & 1 \end{bmatrix} \end{array}$$

CR = 0.02

The Crisp Pair-wise Comparison among objectives of Expert 7

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 2 & 1 & 6 & 7 \\ 1/2 & 1 & 1 & 5 & 5 \\ 1 & 1 & 1 & 5 & 5 \\ 1/6 & 1/5 & 1/5 & 1 & 1/3 \\ 1/7 & 1/5 & 1/5 & 3 & 1 \end{bmatrix} \end{array}$$

CR = 0.04

The Crisp Pair-wise Comparison among objectives of Expert 8

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 4 & 1 & 6 & 7 \\ 1/4 & 1 & 1 & 3 & 5 \\ 1 & 1 & 1 & 5 & 5 \\ 1/6 & 1/3 & 1/5 & 1 & 1 \\ 1/7 & 1/5 & 1/5 & 1 & 1 \end{bmatrix} \end{array}$$

CR = 0.03

The Crisp Pair-wise Comparison among objectives of Expert 9

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 3 & 1 & 6 & 7 \\ 1/3 & 1 & 1 & 3 & 5 \\ 1 & 1 & 1 & 6 & 8 \\ 1/6 & 1/3 & 1/7 & 1 & 1 \\ 1/7 & 1/5 & 1/8 & 1 & 1 \end{bmatrix} \end{array}$$

CR = 0.02

To sum up assessment from 9 experts through the fuzzy matrix

Table 5.8. The fuzzy matrix among objectives of scenario 1

	Z_1	Z_2	Z_3	Z_4	Z_5
Z_1	(1 1 1)	(1 1.22 4)	(1 3.27 6)	(3 6.25 9)	(1 5.73 9)
Z_2	(0.25 0.81 1)	(1 1 1)	(1 1.86 6)	(2 5.19 9)	(2 5.27 9)
Z_3	(0.16 0.30 1)	(0.16 0.53 1)	(1 1 1)	(1 2.77 6)	(1 3.20 6)
Z_4	(0.11 0.16 0.33)	(0.11 0.19 0.5)	(0.16 0.36 1)	(1 1 1)	(0.25 0.62 1)
Z_5	(0.11 0.17 1)	(0.11 0.18 0.5)	(0.16 0.31 1)	(1 1.60 4)	(1 1 1)

$(w_1; w_2; w_3; w_5; w_4) = (0.293; 0.276; 0.221; 0.14; 0.07)$

Scenario 2: More priority for economic development and environmental protection

Economy > Environment > Society: $Z_1 > Z_2 > Z_5 > Z_4 > Z_3$

The Crisp Pair-wise Comparison among objectives of Expert 1

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 5 & 1 & 3 & 3 \\ 1/5 & 1 & 1/9 & 1/3 & 1/7 \\ 1/2 & 9 & 1 & 3 & 3 \\ 1/3 & 3 & 1/3 & 1 & 0.5 \\ 1/3 & 7 & 1/3 & 2 & 1 \end{bmatrix} \end{array}$$

CR = 0.04

The Crisp Pair-wise Comparison among objectives of Expert 2

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 6 & 3 & 3 & 3 \\ 1/6 & 1 & 1/6 & 1 & 1/5 \\ 1/3 & 6 & 1 & 3 & 3 \\ 1/3 & 1 & 1/3 & 1 & 1 \\ 1/3 & 5 & 1/3 & 1 & 1 \end{bmatrix} \end{array}$$

CR = 0.08

The Crisp Pair-wise Comparison among objectives of Expert 3

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 6 & 1 & 5 & 5 \\ 1/6 & 1 & 1/5 & 1/3 & 1/3 \\ 1 & 5 & 1 & 8 & 4 \\ 1/5 & 3 & 1/8 & 1 & 1/2 \\ 1/5 & 3 & 1/4 & 2 & 1 \end{bmatrix} \end{array}$$

CR = 0.05

The Crisp Pair-wise Comparison among objectives of Expert 4

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 3 & 1 & 1 & 2 \\ 1/3 & 1 & 1/5 & 1/2 & 1 \\ 1 & 5 & 1 & 1 & 3 \\ 1 & 2 & 1 & 1 & 1/2 \\ 1/2 & 1 & 1/3 & 2 & 1 \end{bmatrix} \end{array}$$

CR = 0.08

The Crisp Pair-wise Comparison among objectives of Expert 5

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 8 & 1 & 3 & 3 \\ 1/8 & 1 & 1/6 & 1/3 & 1/7 \\ 1 & 6 & 1 & 7 & 5 \\ 1/3 & 3 & 1/7 & 1 & 1 \\ 1/3 & 7 & 1/5 & 1 & 1 \end{bmatrix} \end{array}$$

CR = 0.07

The Crisp Pair-wise Comparison among objectives of Expert 6

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 7 & 1 & 6 & 3 \\ 1/7 & 1 & 1/5 & 1 & 1/5 \\ 1 & 5 & 1 & 4 & 4 \\ 1/6 & 1 & 1/4 & 1 & 1/3 \\ 1/3 & 5 & 1/4 & 3 & 1 \end{bmatrix} \end{array}$$

CR = 0.04

The Crisp Pair-wise Comparison among objectives of Expert 7

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 9 & 3 & 7 & 3 \\ 1/9 & 1 & 1/5 & 1/5 & 1/3 \\ 1/3 & 5 & 1 & 5 & 3 \\ 1/7 & 5 & 1/5 & 1 & 1/2 \\ 1/3 & 3 & 1/3 & 2 & 1 \end{bmatrix} \end{array}$$

CR = 0.08

The Crisp Pair-wise Comparison among objectives of Expert 8

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 7 & 3 & 7 & 3 \\ 1/7 & 1 & 1/5 & 1/3 & 1/3 \\ 1/3 & 5 & 1 & 5 & 3 \\ 1/7 & 3 & 1/5 & 1 & 1/2 \\ 1/3 & 3 & 1/3 & 2 & 1 \end{bmatrix} \end{array}$$

CR = 0.06

The Crisp Pair-wise Comparison among objectives of Expert 9

$$\begin{array}{c} \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \end{array} \begin{array}{c} \begin{array}{ccccc} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 \end{array} \\ \begin{bmatrix} 1 & 7 & 3 & 5 & 3 \\ 1/7 & 1 & 1/5 & 1/3 & 1/3 \\ 1/3 & 5 & 1 & 6 & 3 \\ 1/5 & 3 & 3 & 1 & 1 \\ 1/3 & 3 & 1/3 & 1 & 1 \end{bmatrix} \end{array}$$

CR = 0.06

To sum up the assessment of 9 experts through the fuzzy matrix

Table 5.9.The fuzzy matrix among objectives of scenario 2

	Z₁			Z₂			Z₃			Z₄			Z₅		
Z_1	(1	1	1)	(1	1.629	4)	(2	6.19	9)	(1	3.878	8)	(1	3.035	6)
Z_2	(0.25	0.613	1)	(1	1	1)	(4	5.558	9)	(1	4.064	9)	(2	3.385	6)
Z_3	(0.111	0.162	0.5)	(0.111	0.18	0.25)	(1	1	1)	(0.167	0.42	1)	(0.125	0.278	1)
Z_4	(0.125	0.258	1)	(0.111	0.246	1)	(1	2.378	6)	(1	1	1)	(0.25	0.602	1)
Z_5	(0.167	0.329	1)	(0.167	0.295	0.5)	(1	3.591	8)	(1	1.661	4)	(1	1	1

$(w_1; w_2; w_5; w_4; w_3)$ = (0.284; 0.277; 0.211; 0.17; 0.058)

Scenario 3: The same priority for all development objectives

Economy = Society = Environment : $Z_1 = Z_2 = Z_3 = Z_4 = Z_5$

$w_1 = w_2 = w_3 = w_4 = w_5 = 0.2$

Scenario 4: Only income objective

The maximize Income, w = 1.

Scenario 5: Only Benefit per cost ratio objective

The maximize Benefit per cost ratio, w = 1.

Scenario 6: Only Employment objective

The maximize Employment, w = 1.

Scenario 7: Only highly suitable area of land physical suitability objective

The maximize highly suitable area of land physical suitability, w = 1.

Scenario 8: Only protect environment objective

The maximize protect the environment, w = 1.

5.9.2. The scenarios in the allocation of agricultural land-use

Table 5.10. The optimal linear programming functions scenarios and the constraints

Scenario	Linear programming functions					Constraints			
	Z_1	**Z_2**	**Z_3**	**Z_4**	**Z_5**	**C_1**	**C_2**	**C_3**	**C_4**
1	w=0.293	w=0.276	w=0.221	w=0.07	w=0.14	☑	☑	☑	☑
2	w=0.284	w=0.277	w=0.058	w=0.17	w=0.221	☑	☑	☑	☑
3	w = 0.2	w = 0.2	w = 0.2	w = 0.2	w = 0.2	☑	☑	☑	☑
4	w = 1	0	0	0	0	☑	☑	☑	☑
5	0	w = 1	0	0	0	☑	☑	☑	☑
6	0	0	w = 1	0	0	☑	☑	☑	☑
7	0	0	0	w = 1	0	☑	☑	☑	☑
8	0	0	0	0	w = 1	☑	☑	☑	☑

Scenario 1: The fuzzy multi-objective u_1

$$u_1 = \left(\frac{0.293Z_1}{6{,}102{,}991}\right) + \left(\frac{0.267Z_2}{45{,}169}\right) + \left(\frac{0.221Z_3}{611{,}804{,}080}\right) + \left(\frac{0.077Z_4}{40{,}479}\right) + \left(\frac{0.14Z_5}{7{,}851{,}918}\right) \rightarrow Max \quad (5.16)$$

Scenario 2: The fuzzy multi-objective u_2

$$u_2 = \left(\frac{0.284Z_1}{6{,}102{,}991}\right) + \left(\frac{0.277Z_2}{45{,}169}\right) + \left(\frac{0.058Z_3}{611{,}804{,}080}\right) + \left(\frac{0.177Z_4}{40{,}479}\right) + \left(\frac{0.211Z_5}{7{,}851{,}918}\right) \rightarrow Max \quad (5.17)$$

Scenario 3: The fuzzy multi-objective u_3

$$u_3 = \left(\frac{0.2Z_1}{6{,}102{,}991}\right) + \left(\frac{0.2Z_2}{45{,}169}\right) + \left(\frac{0.2Z_3}{611{,}804{,}080}\right) + \left(\frac{0.2Z_4}{40{,}479}\right) + \left(\frac{0.2Z_5}{7{,}851{,}918}\right) \rightarrow Max \quad (5.18)$$

Scenario 4: The maximize Income (Million VND/ha/year)

$$u_4 = Z_1 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(1)} X_{ijk} \rightarrow Max \quad (5.19)$$

Scenario 5: The maximize Benefit per cost ratio (B/C)

$$u_5 = Z_2 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(2)} X_{ijk} \rightarrow Max \quad (5.20)$$

Scenario 6: The maximize Employment

$$u_6 = Z_3 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(3)} X_{ijk} \rightarrow Max \quad (5.21)$$

Scenario 7: The maximize highly suitable area of land physical suitability

$$u_7 = Z_4 = \sum_{i=1}^{5} \sum_{j=1}^{1} \sum_{k=1}^{13} b_{ijk(4)} X_{ijk} \rightarrow Max \quad (5.22)$$

Scenario 8: The maximize protect the environment

$$u_8 = Z_5 = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{13} b_{ijk(5)} X_{ijk} \rightarrow Max \quad (5.23)$$

Table 5.11 shows the optimal area of land use types and scenarios, respectively. All of the scenarios get all agricultural area with 118,297.07 ha except Scenario 7 because it only maximizes highly suitable (S1) area. The Shrimp – Rice rotation crops (LUT 3) is chosen in most scenarios, the similar maximum area 93,285.16 ha in scenario 6 (The maximize Employment) and scenario 8 (The maximize protect environment). The opposite thing is visible in two rice crops (LUT 2). LUT 2 is only present in scenario 2,5,7. Considering fuzzy multi-objective linear programming, Scenario 2 get more LUTs (LUT 1, LUT 2, LUT 3, LUT 4) in comparison with scenario 1 (LUT 1, LUT 2). Scenario 2 is ranked for interactive fuzzy satisfying of five objectives Z_1, Z_2, Z_3, Z_5, Z_4 with its weights 0.293, 0.276, 0.221, 0.14, 0.07 respectively.

Table 5.11. The optimal area of land use types and scenarios, respectively

Scenarios	LUT 1	LUT 2	LUT 3	LUT 4	LUT 5	Total (ha)
1	35,085.25	0	83,211.82	0	0	118,297.07
2	11,559.44	23,525.81	44,838.06	38,373.76	0	118,297.07
3	11,559.44	0	44,623.53	38,588.29	23,525.81	118,297.07
4	5,018.80	0	44,838.06	38,373.76	30,066.45	118,297.07
5	0	35,085.25	83,211.82	0	0	118,297.07
6	0	0	93,285.16	4,518.45	20,493.46	118,297.07
7	3,853.15	3,853.15	0	38,588.29	3,853.15	50,147.73
8	0	0	93,285.16	0	25,011.91	118,297.07

Table 5.12 and Figure 5.13 show the maximum value of the single and multi-objective objective linear programming of eight scenarios. The value of scenario 4,5,6,7,8 is most significant for every of its single objectives. It is proper for a short planning period, and then planners desire to achieve a priority target on economic development, to give employment to agricultural labor or to decrease the impact on the environment. To compare the value of three scenarios (1,2,3), scenario 3 is a balance between scenario 1 and 2, the weight is equal for five objectives, with 0.2. Scenario 3 is suitable for the fair agricultural planning with many objectives. However, for sustainable planning in the extended period, scenario 1 and 2 are better choices. In which, scenario 2 with priority ranking is economy, environment, society. It is optimized for all five objectives and four constraints in FMOLP, the final value of maximizing the highly suitable area of land physical suitability (49,933) and diversity of LUTs (LUT 1, LUT 2, LUT 3, LUT 4). Scenario 2 is the best land use allocation towards sustainable development.

Table 5.12. The final value linear programming of objectives

Scenarios	Z_1	Z_2	Z_3	Z_4	Z_5
1	8,622,618	50,715	16,748,207	11,559	8,188,321
2	8,610,997	45,010	14,628,774	49,933	6,886,286
3	9,475,691	34,803	15,750,504	50,148	7,464,117
4	9,660,436	30,770	15,856,122	49,933	7,788,906
5	7,694,748	54,802	15,590,394	11,559	8,998,089
6	8,297,448	33,185	17,656,236	13,964	9,714,151
7	3,557,445	9,633	5,852,156	50,148	2,062,084
8	8,433,069	34,653	17,647,199	9,669	9,914,002

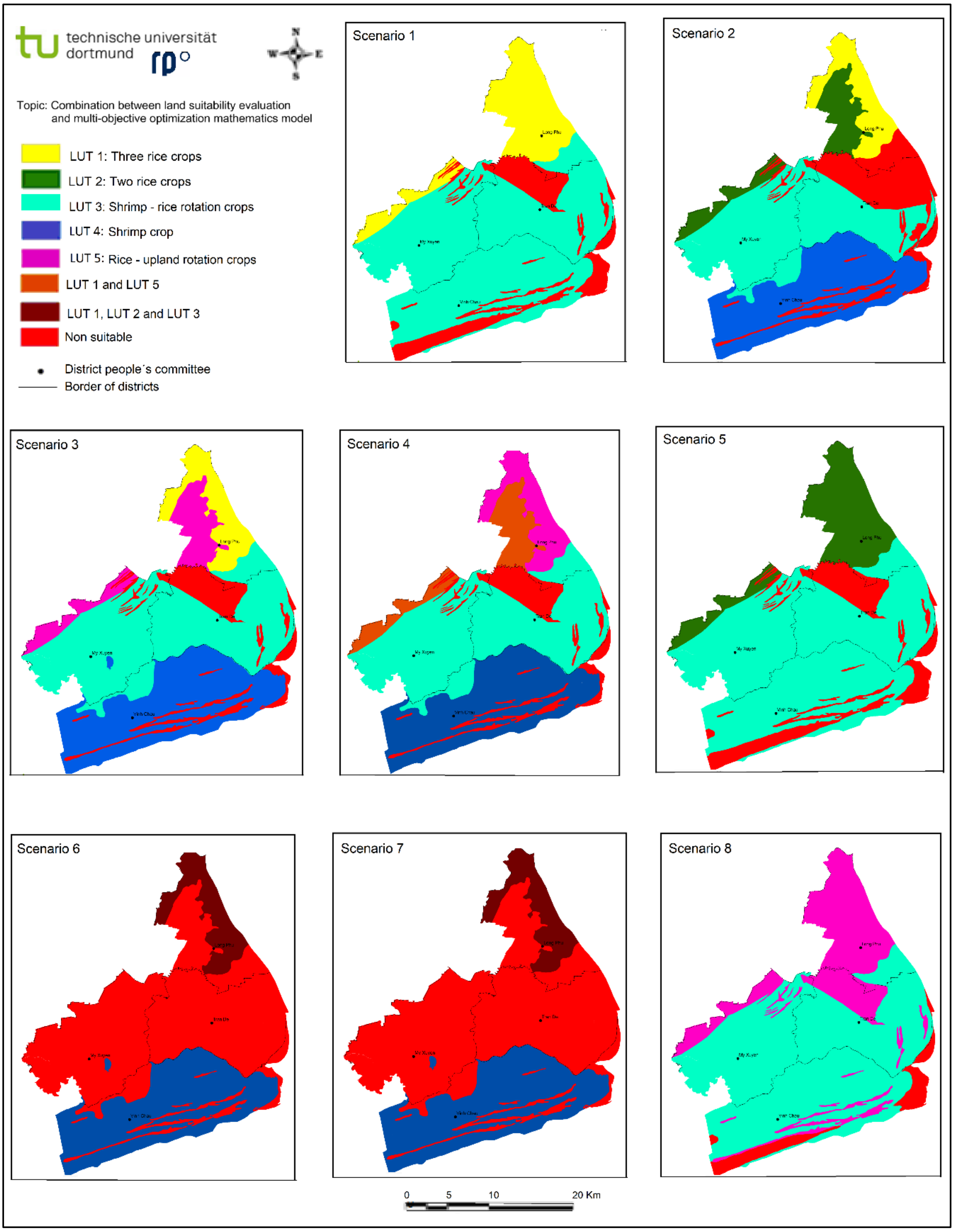


Figure 5.13. Spatial planning of eight scenarios of FMOLP

5.10. Comparison of the agricultural land use change in 2015, FMOLP and master plan 2020

There are two conditions that have to be addressed for useful planning: The ones that are necessary for land use change or to restrict some changes which must be accepted by the people involved. The second condition needs political power to set the plan into effect. If two conditions are not satisfied, planners should organise an awareness campaign or establish performance areas in order to create effective planning (FAO, 1993).

Rendered on a bar graph (Figure 5.14) is data about the rice crops area in 2015 (DONRE, 2015), FMOLP and master plan 2020 (The Government, 2013). Slightly fewer area is occupied by rice in the master plan of 2020 than in 2015, five years ago, with figures standing at 45,970 ha and 52,338 ha, respectively. Similarly, there was a lesser tendency of the rice area in FMLOP to get on the Scenario 1,2,3,4 and 5 as 38,085 ha, and 45,970 ha of the rice area of the master plan in 2020 did so. In scenario 7, there was a significant difference in the rice area in FMLOP in comparison with the rice area of the master plan in 2020, with 11,559 ha and 45,970 ha. It can be accurately generalized that of the rice area in FMLOP of scenario 1,2,3,4 and 5 were substantially more to getting scenario 6, 7 and 8.

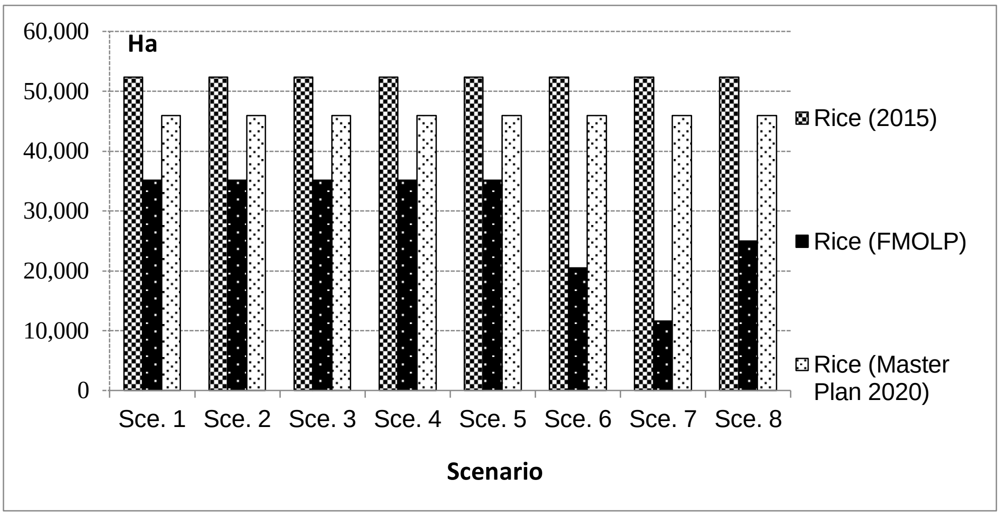


Figure 5.14. To compare the rice crops area in 2015, FMOLP and master plan 2020

The bar graph at hand was illustrated to compare the aquaculture area in 2015 (DONRE, 2015), FMOLP and of the master plan 2020 (The Government, 2013). In comparison, the aquaculture area of FMOLP was overwhelmingly greater than the aquaculture area in 2015 and the aquaculture area of the master plan 2020 in all scenarios except scenario 7. There was a slight rise of the aquaculture area in 2015 in comparison with the aquaculture area of the master plan in 2020, with 54,573 ha and 58,224 ha. (Figure 5.15).

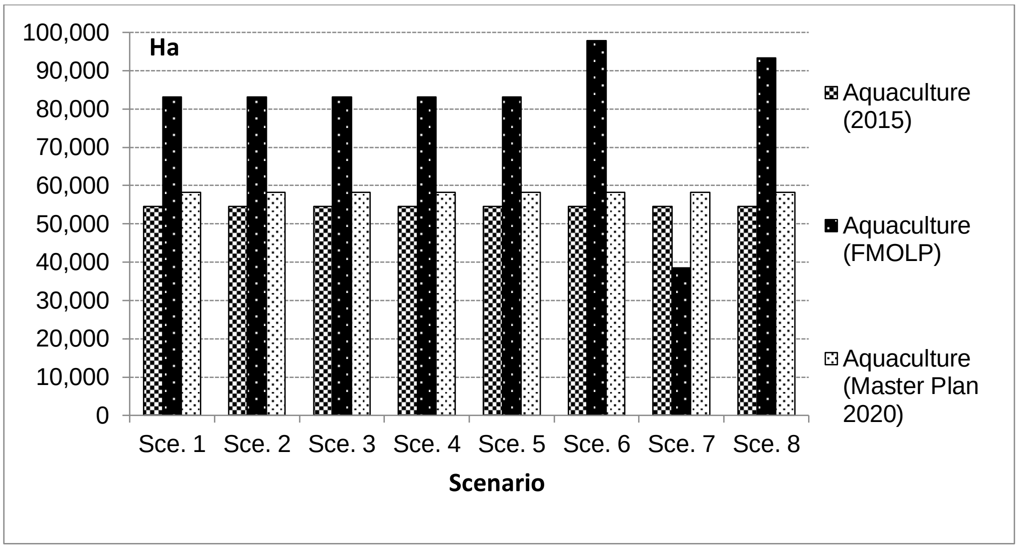


Figure 5.15. To compare the aquaculture area in 2015, FMOLP and master plan 2020

In conclusion, with the larger aquaculture area in FMLOP than in the master plan 2020, and with the smaller amount of rice area in FMLOP than in the master plan 2020, it shows, it is a better trend for sustainable agricultural land-use planning. Besides, it is completely suitable with the decision of the National Assembly Standing Committee (2016) that forced to switch to other crops or aquaculture. The National Assembly has approved the resolution on revising the land use master plan until 2020, and the national land use plan for 2016-2020 in the Mekong Delta, around 400 thousand ha of rice crop will be set aside for other uses amid frequent drought and salinity. According to Vietnam´s climate change scenario, sea level will rise by 12 cm until 2020, affecting 6,000 Ha of rice crops, including 4,000 ha in the Mekong Delta. Therefore, The National Assembly has approved the land use master plan for 2020. Approximately 400,000 ha of rice crop change to another crop in the Mekong Delta. This study suggests changing land use planning by Scenario 2 for the 2020- 2025 period in this study area. According to The National Assembly (2013), adjustment of a master plan on land use is only conducted in the following cases: There are adjustments to the strategies for socio-economic development, national defence, and security or master plans for the development of socio-economic regions and such adjustments result in change of the land use structure. Natural disasters or wars result in changes in the land use purposes, structure, locations and area. There are adjustments in the master plan on land use of the immediate superior level which affect the master plan on land use of the concerned level. There are adjustments to local administrative boundaries.

5.11. Comparison between land sustainable suitability and FMOLP

The result of land sustainable suitability in the Fuzzy environment by Lukasiewicz operator divides LUT into 11 regions, every region shows the differences of suitability classification from S1 to N. This is a flexible method for decision makers in land use planning. It is also suitable for the master plan at the district level in the 10 year periods because there are more options for the farmer and local government to choose the kind of LUT in the unstable market of agricultural products in Viet Nam and the increase of salt water intrusion in the coastal area.

Regarding the result of land use planning in FMLOP by 8 scenarios, its spatial planning is more detailed for LUT, with the specific area. It is also an optimization for multi-objective analysis by applying a compromise index that incorporates the preferences of decision makers like farmers, local government and experts. FMOLP is an excellent method for land use planning in the short period for 5 years. Depending on the priority target, decision maker can choose the proper scenario.

6. Conclusions

In the previous chapters, there is a brief outline of the fundamental theoretical principles of this study. It presents the main contents which are related to researches on sustainable agricultural land-use planning (see chapter 2). In addition, the study area in four coastal districts of Soc Trang province, soil and water characteristics and the agricultural land use change are described in chapter 3. Chapter 4 provides the methodological framework with the data collection methods, land suitability analysis, combined land physical suitability with FMOLP and FAHP-GDM for this study. By applying these methods in the study area, the results obtained in four coastal districts of Soc Trang province are presented in chapter 5. In the following chapter, the answers to the research questions and the main findings are concluded. Based on the results, the development recommendation and outlook are proposed.

6.1. The answers to the research questions

1) Which method can be applied for land suitability analysis in the crisp and fuzzy environment?

There are methods that have been developed for land suitability analysis. In chapter 2.1, land suitability is described as the process of estimating the possible behaviour of the land when utilized for a particular purpose. It can be carried out in a crisp environment with qualitative and quantitative methods. However, in reality, as spatial objects are not often clear in suitability classification, it is difficult to express them in the crisp set (Thinh & Hedel, 2005). The decision-making problems are very vague and uncertain in a number of ways. Most of the criteria have interdependent and interactive features, so they cannot be evaluated by conventional measuring methods (Chen et al. 2011). It was presented in chapter 2.3 with some main mathematical models by fuzzy set theory. The applications of fuzzy set theory to multi-criteria evaluation methods under the framework of utility theory have proven to be an effective approach (Zhang et al. 2015).

In this study it was found that the method can be applied for land suitability analysis in the crisp and fuzzy environment. By comparison of land physical suitability in the crisp environment (FAO; MCE methods) and the fuzzy environment (Fuzzy operator by Max; Fuzzy operator by Lukasiewicz) presented in chapter 5.4, it can be concluded that the fuzzy set theory expressed land suitability classification (S1, S2, S3, N) continuously, which is a basic premise for defuzzification. Land physical suitability of FAO is not flexible because of the principle of maximizing limit factors. The biophysical land evaluation is too general and static (Trung, 2006). It is difficult to widen the area for land use planning in detail because it could not deal with the quick changes in biophysical conditions due to the conversion of fresh water to brackish water in the study area. It is only proper for land evaluation on a large level, such as a region or nation. Land physical suitability by the MCE method is very general because of the average of all factors. Its results were strongly affected by the priority weights, which reflect the land use planner's perception of the importance of the socio-economic and environmental criteria, and the decision maker's perception of the importance of the planning goals (Trung, 2006). Land physical suitability in the fuzzy environment (with MAX operator) is the priority for some good factors. It is suitable for short land use planning. As a useful method, land physical suitability in the fuzzy environment (with LUKASIEWICZ operator) is interactive for all factors together.

After identifying the best suitable method for land suitability, it is necessary to solve sustainable land suitability with many indicators of the economy, society, natural resources and environment. Therefore, the next research question is raised.

2) How to determine problems of agricultural sustainable land suitability under conditions of uncertainty by multiple objectives?

Land suitability is a critical step in LUP. The advantages and disadvantages of a LUP approach vary depending on the place, time and available data, biophysical characteristics, and prevailing political conditions (Albrecht et al. 1996; Illsley, 2003; Mccall, 2003). Spatial planners have to consider a great number of criteria, objectives and human preferences (Thinh & Hedel, 2005). In chapter 2.2, LUP is the systematic assessment of land and water potential, alternatives for land use and economic and social conditions to select and adopt the best land-use options. In the study area, the increasingly experienced salinity intrusion in freshwater systems can seriously affect agricultural activities and particularly rice production. It leads to land use change presented in chapter 3. Therefore, LUP requires the consideration of multiple objectives, including environmental, ecological, economic, social, and other factors. In this study, there were three main indicators (Economy; Society; Natural resources and environment), and twenty sub-indicators are developed by AHP. To handle the problem of agricultural LUP under conditions of uncertainty, typified by multiple objectives, the fuzzy set theory might be the most common method of dealing with uncertainty (Kahraman, 2008). In particular, to deal with fuzzy problems, membership functions such as linear triangle function were used (Ren et al. 2017). In this work, the fuzzification via membership functions for 4 linguistic terms of suitable level (S1, S2, S3, N) was conducted by using triangular fuzzy number. The next step is the application of the fuzzy LUKASIEWICZ operator for sustainable agricultural land suitability (Chapter 4.2).

The results shown in chapter 5.6 demonstrate their effectiveness in evaluating sustainable land suitability because the evaluation is separate which has more risks for land use and land management. It combined the preferences of multi-objectives by weights and expresses the fuzzy suitability classification effectively in a fuzzy environment. The advantage of this method is that it can reduce the land-use conflicts by AHP. It takes into account the farmers' preference changes and preference conflicts. It would be advantageous for an application in future researches.

In the next step, chapter 4.3 provides the answers to the third question and chapter 5.8 gives the results for the process of the proposed method.

3) How the result of land suitability evaluation should be integrated into a multi-objective optimization model of the allocation of agricultural land-use?

As reviewed in chapter 2.3, the efforts to understand FMOLP models have been proposed to deal with different decision-making situations that involve fuzzy values in objective function parameters, constraints parameters, or goals. In order to bridge these gaps in the previous studies and to effectively allocate and give more detailed scenarios in optimal agricultural land use planning, it is necessary to set variables and constraint functions in FMOLP. The result of land physical suitability in the previous question is the most important tool to compare or match land use requirements with characteristics of different tracts of land. Therefore, the variables of FMOLP are based on the land physical suitability.

The results in chapter 5.8 showed the process of the combination between land physical suitability evaluation and a multi-objective optimization mathematics model to sustainable agricultural land use planning in the study area. The result of land physical suitability evaluation is a first step for the variables of FMOLP. FMOLP is an entirely proper process for sustainable land use planning because it is satisfied for conflicts of interest from qualitative and quantitative objectives by the fuzzy linear membership. The spatial planning for LUTs with eight scenarios optimized the multi-objective base on the constraints. This aims at handling the problem of optimization under conditions of uncertainty typified by multiple objectives as the requirements of socio-economic development and environmental protection to support better agricultural land use planning. It has been demonstrated that explicit and effecting modelling of any decision-making process with FMOLP algorithms improves the effectiveness of the processes.

Based on the FMOLP, the preferences of decision makers using a compromise index were incorporated in the last question.

4) How to satisfy the requirements for DMs in the sustainable agricultural land use planning?

A fundamental problem of decision theory is how to derive weights for a set of activities according to importance (Saaty, 1977) and to identify and explore possible futures is scenarios. Scenario development is a relatively new and thus under-explored method in land use change research, certainly compared to modelling (Kok et al. 2007). FAHP has been playing an increasingly important role in multiple criteria decision-making under uncertainty and has found extensive applications in a wide variety of areas such as supplier selection. Chapter 4.4 presented a detailed methodology, applied for multiple criteria decision-making, it requires accurate weight derivation from fuzzy pairwise comparison matrices. It incorporates the important levels of objectives from many of the expert's assessments to identify compromise indexes.

The results in chapter 5.9 show that the DMs with a satisfactory degree of the preferences propose alternative solutions for better land use planning by incorporating the preferences of DMs using a compromise index to identify weights (w) for 5 objectives by eights scenarios. In the practical situation, all objective functions do not possess same weights. Therefore the weights of the objective functions can be changed according to the requirement of the manager (Shaw et al. 2012). According to the ideas of experts and farmers suggested for agricultural land use planning in the study area, eight scenarios were designed to find the optimization of land use. The proposed method is a useful decision-making tool for the balance of multiple objectives. The results of FAHP demonstrated for better selection problem.

In brief, to satisfy the requirements for DMs in the sustainable agricultural land uses, planning could be concluded mainly from three steps: establishment of a pair-wise and fuzzification pair-wise comparison matrix, summary assessment by the fuzzy matrix and identification weights.

6.2. Development implication

The study presented a full comparison of the agricultural land use change in 2015, FMOLP and the master plan 2020 to provide a better understanding of the different land-use planning underlying FMOLP model. The results of the comparison with the greater aquaculture area in FMLOP than in the master plan in 2020, and with the smaller rice area in the FMOLP than in the master plan in 2020 show, it is a better trend for sustainable agricultural land-use planning. It is entirely suitable with the decision of National Assembly Standing Committee (2016) that forced to switch to other crops or aquaculture of the land use master plan until 2020 and the national land use plan for 2016-2020.

Regarding the results, they can be applied for sustainable agricultural land use planning in the coastal zone, the comparison between land sustainable suitability in the Fuzzy environment by Lukasiewicz operator and FMOLP were considered. Land sustainable suitability in the Fuzzy environment by Lukasiewicz operator is proposed for agricultural land use planning in the extended period 2020 – 2030 (master plan of 10 years) while land use planning in FMOLP for the specific plan in the short period 2020 – 2025 (5 years). Both methods of land sustainable suitability in the fuzzy environment by Lukasiewicz operator and FMOLP create a balance between the land use supply and demand for land use change.

The study has been successful in solving the conflict between economic development and the unstable environment in land use planning. In comparison with other scenarios, scenario 2 could be considered as the best one in achieving the objectives of compact multi-objectives with the preferences economically efficient development, pleasant environment and social issues.

Using a combination of land suitability and the FMOLP a new plan model for an effective agricultural land-use can be constructed.

6.3. Outlooks for further works

There were some quick changes on three different ecological zones by the trend of sea level rise, salt water intrusion, longer dry seasons and shorter rainy seasons with less rainfall. Therefore, for the future development, the master plan of this study area needs to be strictly implemented for identifying the suitable spatial allocation for LUTs. Especially, the local government should switch to 2-3 rice crops to shrimp – rice rotation crops and shrimp crop. The results of study showed that the farmers adapt with the problems on changing land use on three different ecological zones (salt, fresh and brackish water). This solution does not require too much cost but will give practical effects to the affected people. Ensuring a stable production and bringing economic efficiency are the primary goals (Vu et al. 2013).

Salinity and salty time management plans for salt aquaculture must be considered (Phong et al. 2016). These plans should be frequently evaluated and modified for land use planning.

Next researches are necessary because the land use planning needs to appropriately cope with the impact of salinity intrusion, salty time and flooding at difference hot spot or vulnerability areas. The results could be expected to be able to provide a framework for sustainable agricultural land use planning in the coastal areas in Viet Nam. Although there are certain differences between other coastal zones in Viet Nam, the area of the coastal zone faces the same challenges. For this reason, being able to successfully provide the combination of land suitability and FMOLP for the coastal zone in Soc Trang province would be beneficial for the adoption of the approach in the other coastal zone for land use planning.

References

Ã, D. D. R., Mayol, F., Fernandez, M., & Jr, D. D. R. (2004). A land evaluation decision support system (Micro LEIS DSS) for agricultural soil protection With special reference to the Mediterranean region. Environmental Modelling & Software, 19, 929–942. https://doi.org/10.1016/j.envsoft.2003.10.006

Abdi, E., Majnounian, B., Darvishsefat, A., Mashayekhi, Z., & Sessions, J. (2009). A GIS-MCE based model for forest road planning. Journal of Forest Science, 55(4), 171–176. https://doi.org/10.1007/s10661-015-4876-9

Albrecht, D., Eller, E., Fleddermann, A., Janz, K., Künzel, W., & Riethmüller, R. (1996). Experiences of Land Use Planning in Asian Projects. . Selected Insights. The Working Group on Land Use Planning for the Asian-Pacific Region, GTZ.

Amini, A. (2015). Application of fuzzy multi-objective programming in optimization of crop production planning. Asian Journal of Agricultural Research, 9(5), 208–222. https://doi.org/10.3923/ajar.2015.208.222

Bagheri Bodaghabadi, M., Martínez-Casasnovas, J. A., Khakili, P., Masihabadi, M. H., & Gandomkar, A. (2015). Assessment of the FAO traditional land evaluation methods, A case study: Iranian Land Classification method. Soil Use and Management, 31(3), 384–396. https://doi.org/10.1111/sum.12191

Baroudy, A. A. El. (2016). Catena Mapping and evaluating land suitability using a GIS-based model. Catena, 140, 96–104. https://doi.org/10.1016/j.catena.2015.12.010

Bill, R., Nash, E., & Grenzdörffer, G. (2011). GIS in Agriculture. In Springer Handbook of Geographic Information (pp. 461–476). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-72680-7_24

Borges, A. R., & Antunes, C. H. (2002). A weight space-based approach to fuzzy multiple-objective linear programming. Decision Support Systems, 34(4), 427–443. https://doi.org/10.1016/S0167-9236(02)00068-4

Can Tho University. (2016). Solutions for preventing drought and saltwater intrusion for crops and livestock in the Mekong Delta region. Retrieved August 1, 2017, from http://ctu.edu.vn/en/news_det.php?id=731&act=page&page=15#me

Carlsson, C., & Fullér, R. (1995). Multiple criteria decision making: The case for interdependence. Computers & Operations Research, 22(3), 251–260. https://doi.org/10.1016/0305-0548(94)E0023-Z

Chang, C. W., Wu, C. R., & Lin, H. L. (2009). Applying fuzzy hierarchy multiple attributes to construct an expert decision making process. Expert Systems with Applications, 36(4), 7363–7368. https://doi.org/10.1016/j.eswa.2008.09.026

Chang, & Ko. (2014). An interactive dynamic multi-objective programming model to support better land use planning. Land Use Policy, 36, 13–22. https://doi.org/10.1016/j.landusepol.2013.06.009

Chang, N. B., Wen, C. G., & Wu, S. L. (1995). Optimal Management of Environmental and Land Resources in a Reservoir Watershed By Multiobjective Programming. Journal of Environmental Management, 44, 145–161.

Chen, C. C., McCarl, B., & Chang, C. C. (2012). Climate change, sea level rise and rice: Global market implications. Climatic Change, 110(3–4), 543–560. https://doi.org/10.1007/s10584-011-0074-0

Chen, Lien, H.-P., Liu, C.-H., Liou, J. J. H., Tzeng, G.-H., & Yang, L.-S. (2011). Fuzzy MCDM approach for selecting the best environment-watershed plan. Applied Soft Computing Journal, 11(1), 265–275. https://doi.org/10.1016/j.asoc.2009.11.017

Dent, D., & Young, A. (1981). Soil survey and land evaluation. George Allen & Unwin.

Dinh, L. C., & Duc, T. T. (2012). Integration of gis, group AHP and TOPSIS in evaluating sustainable land-use management. In International Symposium on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences 2012.

DONRE - Department of Natural Resources and Environment in Soc Trang. (2008). Monitoring of changing and assessing soil, water qualities in the shrimp-rice, extensive shrimp and intensive shrimp farming systems in the coastal area of Soc Trang province. A scientific cooperation program between Soc Trang Department of Natural Resources and Environment and College of Agriculture and Applied Biology, Can Tho University April from 2006 to September 2008.

DONRE - Department of Natural Resources and Environment in Soc Trang. (2010). The land-related changes between three inventory times 2000, 2005 and 2010.

DONRE - Department of Natural Resources and Environment in Soc Trang. (2015). Land Statistics and inventories to December 31st 2014.

Eldrandaly, K., Eldin, N., Sui, D., Shouman, M., & Nawara, G. (2005). Integrating GIS and MCDM Using COM Technology. The International Arab Journal of Information Technology, 2(2), 6. Retrieved from http://www.google.com/url?sa=t&source=web&cd=1&ved=0CB0QFjAA&url=http://www.ccis2k.org/iajit/PDF/vol.2,no.2/10-elderandely.pdf&ei=LWHWTbOrN4Sw8QPDq-SECw&usg=AFQjCNE2W8h9P_RLHVIpT9vBcYUjagFeOg&sig2=0wSU7Tlvzv8mcGJ2lBqz5A

FAO. (1976). A framework for land evaluation. Rome: Food and Agricultural Organization of the United Nations. FAO soils bulletin n.32. https://doi.org/M-51

FAO. (1983). Guidelines: land evaluation for rainfed agriculture, FAO Soils Bulletin., No. 52., FAO, Rome, 237 pp.

FAO. (1993). Guidelines for land-use planning. Food and Agricultural Organization of the United Nations. FAO Development Series.

FAO. (2007). Land evaluation. Towards a revised framework. Land and Water discussion paper (Vol. 6). Rome.

FAO and UNEP. (1999). The future of our land: facing the challenge. Guidelines for Intergrated Planning for Sustainable Management of Land Resources.

General Statistics Office. (2014). Statistical Hand Book of Vietnam 2014.

GIZ. (2012). Land Use Planning, 1–268. Retrieved from http://www.giz.de/expertise/downloads/Fachexpertise/giz2012-en-land-use-planning-manual.pdf

Hoosbeek, M. R., & Bryant, R. B. (1992). Towards the quantitative modeling of pedogenesis - a review, (July 2015). https://doi.org/10.1016/0016-7061(92)90083-J

Illsley, B. M. (2003). Fair participation — a Canadian perspective. Land Use Policy, 20, 265–273. https://doi.org/10.1016/S0264-8377(03)00024-3

Jager, R. (1995). Fuzzy Logic in Control. Delft TU Publisher, Delft, The Netherlands.

Jankowski, P. (1995). Integrating geographical information systems and multiple criteria decision-making methods. International Journal of Geographical Information Systems, 9(3), 251–273. https://doi.org/10.1080/02693799508902036

Kahraman, C. (2008). Fuzzy Multi-Criteria Decision Making. (P. M. Pardalos & Z. Du Ding, Eds.), Springer Optimization and Its Applications (Vol. 16). Springer. https://doi.org/10.1007/978-0-387-76813-7

Kahraman, C., Ulukan, Z., & Tolga, E. (1994). Fuzzy Multiobjective Linear-Programming-Based Justification Of Advanced Manufacturing Systems. In IEEE International Engineering and Management Conference (IEMC, 96). Proceedings, pp. 226–232.

Khang, N. D., Kotera, A., Sakamoto, T., & Yokozawa, M. (2008). Sensitivity of Salinity Intrusion to Sea Level Rise and River Flow Change in Vietnamese Mekong Delta-Impacts on Availability of Irrigation Water for Rice Cropping. Journal of Agricultural Meteorology, 64(3), 167–176. https://doi.org/10.2480/agrmet.64.3.4

Kiet, N. H. (2008). Soil and water qualities in the shrimp culture systems at My Xuyen, Long Phu, Vinh Chau district, Soc Trang province. Master thesis. Library of College of Agriculture and Applied Biology, Can Tho University.

Klir, G. J., & Yuan, B. (1995). Fuzzy sets and fuzzy logic, theory and applications. Englewood Cliffs, NJ: Prentice-Hall.

Kok, K., Verburg, P. H., & Veldkamp, T. (A). (2007). Integrated Assessment of the land system: The future of land use. Land Use Policy, 24(3), 517–520. https://doi.org/10.1016/j.landusepol.2006.04.007

Kotera, A., Sakamoto, T., Nguyen, D. K., & Yokozawa, M. (2008). Regional consequences of seawater intrusion on rice productivity and land use in coastal area of the mekong river delta. Japan Agricultural Research Quarterly, 42(4), 267–274. https://doi.org/10.6090/jarq.42.267

Lai, S. K. (1995). A preference-based interpretation of AHP. Omega, 23(4), 453–462. https://doi.org/10.1016/0305-0483(95)00025-J

Lai, Y.-J., & Hwang, C.-L. (1992). Fuzzy mathematical programming. In Fuzzy Mathematical Programming (pp. 74–186). Springer.

Lai, Y.-J., & Hwang, C.-L. (1994). Fuzzy multiple objective decision making: Methods and Applications. In Fuzzy Multiple Objective Decision Making. Springer-Verlag, Berlin.

Liang, T.-F. (2009). Fuzzy multi-objective project management decisions using two-phase fuzzy goal programming approach. Computers & Industrial Engineering, 57(4), 1407–1416. https://doi.org/10.1016/j.cie.2009.07.010

Liang, T. F. (2006). Distribution planning decisions using interactive fuzzy multi-objective linear programming. Fuzzy Sets and Systems, 157(10), 1303–1316. https://doi.org/10.1016/j.fss.2006.01.014

Machin, J., & Navas, A. (1995). Land evaluation and conservation of semiarid agrosystems in Zaragoza using an expert evaluation system and GIS. Land Degradation & Rehabilitation, 6(April), 203–214.

Maddahi, Z., Jalalian, A., Masoud, M., & Zarkesh, K. (2017). Land Suitability Analysis for Rice Cultivation Using a GIS-based Fuzzy Multi-criteria Decision Making Approach : Central Part of Amol District , Iran. Soil & Water Resources, 2017(1), 29–38. https://doi.org/10.17221/1/2016-SWR

Malczewski, J. (1999). GIS and multicriteria decision analysis. John Wiley & Sons.

Malczewski, J. (2006). GIS-based multicriteria decision analysis: a survey of the literature. International Journal of Geographical Information Science, 20(7), 703–726. https://doi.org/10.1080/13658810600661508

McBratney, A. B., & Odeh, I. O. A. (1997). Application of fuzzy sets in soil science: Fuzzy logic, fuzzy measurements and fuzzy decisions. Geoderma, 77(2–4), 85–113. https://doi.org/10.1016/S0016-7061(97)00017-7

Mccall, M. K. (2003). Seeking Good Governance in Participatory-GIS : A Review of Processes and Governance Dimensions in Applying GIS to participatory spatial planning. Habitat International, 27(June 2017), 549–673. https://doi.org/10.1016/S0197-3975(03)00005-5

Minh, V. Q., Tri, L. Q., Vu, P. T., & Dung, T. Van. (2016). The Conversion of Mekong Delta soil map legend classified by the WRB/FAO 1998 system into the WRB/FAO 2006 system. Can Tho University Journal of Science, 2016(4), 10–21. https://doi.org/10.22144/ctu.jsi.2016.098

National Assembly Standing Committee. (2016). Vietnam approves land use plan for 2016-2020: less land for rice - VnExpress International. Retrieved August 1, 2017, from http://e.vnexpress.net/news/news/vietnam-approves-land-use-plan-for-2016-2020-less-land-for-rice-3384197.html

Nguyen Hieu Trung. (2006). Comparing land use planning approaches in the Mekong Delta - VietNam. PhD thesis Wageningen University, The Netherlands.

Niacşu, L., Ioniţă, I., & Curea, D. (2015). Optimum agricultural land use in the hilly area of eastern Romania. Case study: Pereschiv catchment. Carpathian Journal of Earth and Environmental Sciences, 10(1), 183–192.

Önüt, S., Efendigil, T., & Soner Kara, S. (2010). A combined fuzzy MCDM approach for selecting shopping center site: An example from Istanbul, Turkey. Expert Systems with Applications, 37(3), 1973–1980. https://doi.org/10.1016/j.eswa.2009.06.080

Parry, J. A., Ganaie, S. A., & Bhat, M. S. (2018). GIS based land suitability analysis using AHP model for urban services planning in Srinagar and

Jammu urban centers of J & K , India. Journal of Urban Management, 7(2), 46–56. https://doi.org/10.1016/j.jum.2018.05.002

Pedrycz, W., & Gomide, F. (1998). An Introduction to Fuzzy Sets: Analysis and Design. MIT Press, Cambridge.

Phong, N. D., Wassmann, R., Tri, L. Q., Hien, N. X., Lang, N. T., Hoa, L. Van, … Phung, C. Van. (2016). Climate change affecting land use in the Mekong Delta: Adaptation of rice- based cropping systems (CLUES). ACIAR GPO Box 1571 Canberra ACT 2601 Australia.

Prakash, T, N. (2003). Land Suitability Analysis for Agricultural Crops : A Fuzzy Multicriteria Decision Making Approach. Geo-Information Science, 1–57.

Ren, C., Guo, P., Tan, Q., & Zhang, L. (2017). A multi-objective fuzzy programming model for optimal use of irrigation water and land resources under uncertainty in Gansu Province, China. Journal of Cleaner Production, 164, 85–94. https://doi.org/10.1016/j.jclepro.2017.06.185

Renaud, F. G., Le, T. T. H., Lindener, C., Guong, V. T., & Sebesvari, Z. (2015). Resilience and shifts in agro-ecosystems facing increasing sea-level rise and salinity intrusion in Ben Tre Province, Mekong Delta. Climatic Change, 133(1), 69–84. https://doi.org/10.1007/s10584-014-1113-4

Rossiter, D. G. (1990). ALES: a framework for land evaluation using a microcomputer. Soil Use and Management, 6(1), 7–20.

Rossiter, D. G. (1995). Economic land evaluation: why and how. Soil Use and Management, 11(3), 132–140. https://doi.org/10.1111/j.1475-2743.1995.tb00511.x

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, 15(3), 234–281.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. International Journal of Services Sciences, 1(1), 83–98. https://doi.org/10.1504/IJSSCI.2008.017590

Saaty, T. L., & Vargas, L. G. (2012). Models , Methods , Concepts & Applications of the Analytic Hierarchy Process. Springer New York Heidelberg Dordrecht

London.

Sakawa, M. (2002). Genetic algorithms and fuzzy multi-objective optimization. Kluwer Academic Publishers, USA.

Sakawa, M., & Kato, K. (2009). An interactive fuzzy satisficing method for multiobjective nonlinear integer programming problems with block-angular structures through genetic algorithms with decomposition procedures. Advances in Operations Research, 2009, 1–17. https://doi.org/10.1155/2009/372548

Sari, B., Sen, T., & Kilic, S. E. (2008). Ahp model for the selection of partner companies in virtual enterprises. International Journal of Advanced Manufacturing Technology, 38(3–4), 367–376. https://doi.org/10.1007/s00170-007-1097-6

Seppelt, R., & Voinov, A. (2003). Optimization methodology for land use patterns - Evaluation based on multiscale habitat pattern comparison. Ecological Modelling, 168(3), 217–231. https://doi.org/10.1016/S0304-3800(03)00138-8

Shaw, K., Shankar, R., Yadav, S. S., & Thakur, L. S. (2012). Supplier selection using fuzzy AHP and fuzzy multi-objective linear programming for developing low carbon supply chain. Expert Systems with Applications, 39(9), 8182–8192. https://doi.org/10.1016/j.eswa.2012.01.149

Srdjevic, B., & Medeiros, Y. D. P. (2008). Fuzzy AHP assessment of water management plans. Water Resources Management, 22(7), 877–894. https://doi.org/10.1007/s11269-007-9197-5

Subiyanto, Hermanto, Arief, U. M., & Nafi, A. Y. (2018). An accurate assessment tool based on intelligent technique for suitability of soybean cropland : case study in Kebumen Regency , Indonesia. Heliyon, 4(e00648). https://doi.org/10.1016/j.heliyon.2018.e00684

Susanto, S., & Bhattacharya, A. (2011). Compromise Fuzzy Multi-Objective Linear Programming (CFMOLP) heuristic for product-mix determination. Computers and Industrial Engineering, 61(3), 582–590. https://doi.org/10.1016/j.cie.2011.04.013

Tanaka, H., & Asai, K. (1984). Fuzzy linear programming problems with fuzzy numbers. Fuzzy Sets and Systems, 13(1), 1–10. https://doi.org/10.1016/0165-0114(84)90022-8

The Government. Master plan on land use to 2020 of Soc Trang province (2013).

The National Assembly Viet Nam. (2013). Land law.

Thinh, N. X., & Hedel, R. (2005). Vergleich zwei räumlicher Bewertungsmethoden - Compromise Programming und regelbasierte hierarchische Fuzzy-Bewertung. Simulation in Umwelt Und Geowissenschaften, 57–66.

Torbert, H. A., Krueger, E., & Kurtener, D. (2008). Soil quality assessment using fuzzy modeling. Institute of Agrophysics, 22, 365–370.

Tri, L. Q., Guong, V. T., Vu, P. T., Binh, N. T. S., Kiet, N. H., & Chien, V. Van. (2008). Evaluating the changes of soil properties and land use at three coastal districts in Soc Trang province. Journal of Science Can Tho University, 9, 59–68.

Triantafilis, J., Ward, W. T., & McBratney, A. B. (2001). Land suitability assessment in the Namoi valley of Australia, using a continuous model. Australian Journal of Soil Research, 39(2), 273–290. https://doi.org/10.1071/SR99087

Turtle, H., Bector, C. R., & Gill, A. (1994). Using Fuzzy Logic in Corporate Finance: An Example of a Multinational Cash Flow Netting Problem. Managerial Finance, 20(8), 36–53. https://doi.org/10.1108/eb018485

USAID. (2016). Development of Rice-Shrimp Farming in Mekong River Delta , Vietnam Development of Rice-Shrimp Farming in Mekong River Delta , Vietnam. The United States Agency for International Development.

Vargahan, B. Z. (2011). Quantitative and Qualitative Land Suitability Evaluation for Maize Cultivation in Ghobadlou Region , Iran. Journal of Applied Sciences, 4(1), 91–104.

Vogel, R. (2008). A Software Framework for GIS-based Multiple Criteria Evaluation of Land Suitability. In 11th AGILE International Conference on Geographic Information Science. Proceedings, pp. 1–12.

Vu, P. T., Huy, V. T., Tri, L. Q., & Vu, P. H. (2013). Change land use farming adaptability of people in the coastal districts Soc Trang and Bac Lieu. Journal of Science, Can Tho University, 26, 46–54.

Wassmann, R., Hien, N. X., Hoanh, C. T., & Tuong, T. P. (2004). Sea level rise affecting the Vietnamese Mekong Delta: water elevation in the flood season and implications for rice production. Climatic Change, 66(1), 89–107.

Werner, A. D., Bakker, M., Post, V. E. A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., … Barry, D. A. (2013). Seawater intrusion processes, investigation and management: Recent advances and future challenges. Advances in Water Resources, 51(January), 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004

Zadeh, L. a. (1965). Fuzzy sets. Information and Control, 8, 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X

Zavala, A. H., Batyrshin, I. Z., Rudas, I. J., Vargas, L. V., & Nieto, O. C. (2009). Parametric operations for digital hardware implementation of fuzzy systems. In Lecture Notes in Computer Science (Vol. 5845 LNAI, pp. 432–443). Springer-Verlag Berlin Heidelberg 2009. https://doi.org/10.1007/978-3-642-05258-3_38

Zeng, X., Kang, S., Li, F., Zhang, L., & Guo, P. (2010). Fuzzy multi-objective linear programming applying to crop area planning. Agricultural Water Management, 98(1), 134–142. https://doi.org/10.1016/j.agwat.2010.08.010

Zhang, J., Su, Y., Wu, J., & Liang, H. (2015). GIS based land suitability assessment for tobacco production using AHP and fuzzy set in Shandong province of China. Computers and Electronics in Agriculture, 114, 202–211. https://doi.org/10.1016/j.compag.2015.04.004

Zimmermann, H. J. (1978). Fuzzy programming and linear programming with several objective functions. Fuzzy Sets and Systems, 1, 45–55. https://doi.org/10.1016/0165-0114(78)90031-3

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Appendix 1. Land physical suitability (FAO) in crisp environment

LU	**Land suitability classification**				
	LUT 1	**LUT 2**	**LUT 3**	**LUT 4**	**LUT 5**
1	N	N	N	N	S3
2	N	N	N	S2	N
3	N	N	N	S1	N
4	N	N	S3	S3	N
5	N	N	N	N	S3
6	S2	S2	N	N	S2
7	S2	S2	N	N	S2
8	S1	S1	N	N	S1
9	N	N	S2	S3	S3
10	N	N	S2	S2	N
11	S2	S2	N	N	S2
12	N	N	S3	S1	N
13	N	N	S3	S1	N
14	N	N	S3	S1	N
15	N	N	S2	S3	S3
16	N	N	S3	S2	N
17	N	N	S2	S2	N
18	N	N	S2	S3	N
19	N	N	N	S3	S3
20	N	N	S3	S2	N
21	N	N	S3	S2	N
22	N	N	S2	S3	N
23	N	N	S3	S2	N
24	N	N	S3	S2	N
25	N	N	S2	S1	N
26	N	N	S2	S3	N
27	N	N	S3	S3	N
28	N	N	N	S3	S3
29	N	N	S3	S2	N
30	N	N	S3	S2	N

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp - rice rotation crops, LUT 4: Shrimp crop, LUT 5: Rice - upland rotation crops

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable

Appendix 2. Land physical suitability (MCE) in crisp environment

LU	Land suitability classification				
	LUT 1	**LUT 2**	**LUT 3**	**LUT 4**	**LUT 5**
1	S2	S2	N	N	S2
2	S3	S3	S2	S2	S3
3	S2	S2	S2	S1	S3
4	S2	S2	S2	S2	S2
5	S2	S2	S2	S3	S2
6	S2	S2	S3	S3	S2
7	S2	S2	S3	S3	S2
8	S1	S1	S3	S3	S1
9	S2	S2	S2	S2	S2
10	S2	S2	S2	S2	S2
11	S2	S2	S2	S2	S2
12	S2	S2	S2	S1	S2
13	S2	S2	S2	S1	S2
14	S2	S2	S2	S1	S2
15	S2	S2	S2	S2	S2
16	S2	S2	S2	S2	S2
17	S2	S2	S2	S2	S2
18	S2	S2	S2	S2	S2
19	S2	S2	S2	S2	S2
20	S2	S2	S2	S2	S2
21	S2	S2	S2	S2	S2
22	S2	S2	S2	S2	S2
23	S2	S2	S2	S2	S2
24	S2	S2	S2	S2	S2
25	S2	S2	S2	S2	S2
26	S2	S2	S2	S2	S2
27	S2	S2	S2	S2	S2
28	S2	S2	S2	S2	S2
29	S2	S2	S2	S2	S2
30	S2	S2	S2	S2	S2

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp - rice rotation crops, LUT 4: Shrimp crop, LUT 5: Rice - upland rotation crops

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable

Appendix 3. Land physical suitability (MAX) in fuzzy environment

LU	**Land suitability classification**				
	LUT 1	**LUT 2**	**LUT 3**	**LUT 4**	**LUT 5**
1	N	N	N	N	S1
2	N	N	N	S2	N
3	N	N	N	S1	N
4	N	N	S3	S2	N
5	N	N	N	N	S2
6	S1	S1	N	N	S2
7	S2	S2	N	N	S2
8	S1	S1	N	N	S1
9	N	N	S2	S2	S2
10	N	N	S1	S2	N
11	S1	S1	N	N	S2
12	N	N	S3	S1	N
13	N	N	S3	S1	N
14	N	N	S3	S1	N
15	N	N	S2	S2	S2
16	N	N	S3	S2	N
17	N	N	S1	S2	N
18	N	N	S2	S3	N
19	N	N	N	S2	S2
20	N	N	S3	S2	N
21	N	N	S3	S2	N
22	N	N	S2	S3	N
23	N	N	S3	S2	N
24	N	N	S3	S2	N
25	N	N	S1	S2	N
26	N	N	S2	S3	N
27	N	N	S3	S2	N
28	N	N	N	S2	S2
29	N	N	S3	S2	N
30	N	N	S3	S2	N

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp - rice rotation crops, LUT 4: Shrimp crop, LUT 5: Rice - upland rotation crops

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable

Appendix 4. Land physical suitability (LUKASIEWICZ) in fuzzy environment

	Land suitability classification				
LU	**LUT 1**	**LUT 2**	**LUT 3**	**LUT 4**	**LUT 5**
1	N	N	N	N	S1
2	N	N	N	S1	N
3	N	N	N	S1	N
4	N	N	S2	S1	N
5	N	N	N	N	S1
6	S1	S1	N	N	S1
7	S1	S1	N	N	S1
8	S1	S1	N	N	S1
9	N	N	S1	S1	S1
10	N	N	S1	S1	N
11	S1	S1	N	N	S1
12	N	N	S1	S1	N
13	N	N	S1	S1	N
14	N	N	S1	S1	N
15	N	N	S1	S1	S1
16	N	N	S1	S1	N
17	N	N	S1	S1	N
18	N	N	S1	S1	N
19	N	N	N	S1	S1
20	N	N	S1	S1	N
21	N	N	S1	S1	N
22	N	N	S1	S1	N
23	N	N	S1	S1	N
24	N	N	S1	S1	N
25	N	N	S1	S1	N
26	N	N	S1	S1	N
27	N	N	S1	S1	N
28	N	N	N	S1	S1
29	N	N	S1	S1	N
30	N	N	S1	S1	N

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp - rice rotation crops, LUT 4: Shrimp crop, LUT 5: Rice - upland rotation crops

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable

Appendix 5. Land economic suitability in Fuzzy operator by Lukasiewicz

LU	Land suitability classification				
	LUT 1	**LUT 2**	**LUT 3**	**LUT4**	**LUT 5**
1	N	N	N	N	S3
2	N	N	N	N	N
3	N	N	N	N	N
4	N	N	S3	N	N
5	N	N	N	N	S3
6	S1	S1	N	N	S2
7	S1	S1	N	N	S2
8	S1	S1	N	N	S1
9	N	N	S1	N	S3
10	N	N	S1	N	N
11	S1	S1	N	N	S2
12	N	N	S3	N	N
13	N	N	S3	N	N
14	N	N	S3	N	N
15	N	N	S1	N	S3
16	N	N	S3	N	N
17	N	N	S1	N	N
18	N	N	S1	N	N
19	N	N	N	N	S3
20	N	N	S3	N	N
21	N	N	S3	N	N
22	N	N	S1	N	N
23	N	N	S3	N	N
24	N	N	S3	N	N
25	N	N	S1	N	N
26	N	N	S1	N	N
27	N	N	S3	N	N
28	N	N	N	N	S3
29	N	N	S3	N	N
30	N	N	S3	N	N

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp - rice rotation crops, LUT 4: Shrimp crop, LUT 5: Rice - upland rotation crops

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable

Appendix 6. Land sustainable suitability in Fuzzy operator by Lukasiewicz

	Land suitability classification				
LU	**LUT 1**	**LUT 2**	**LUT 3**	**LUT 4**	**LUT 5**
1	N	N	N	N	S1
2	N	N	N	S2	N
3	N	N	N	S1	N
4	N	N	S2	N	N
5	N	N	N	N	S1
6	S1	S1	N	N	S1
7	S1	S2	N	N	S1
8	S1	S1	N	N	S1
9	N	N	S1	N	S1
10	N	N	S1	N	N
11	S1	S2	N	N	S1
12	N	N	S2	S1	N
13	N	N	S2	S1	N
14	N	N	S2	S1	N
15	N	N	S1	N	S1
16	N	N	S2	S2	N
17	N	N	S1	S2	N
18	N	N	S1	N	N
19	N	N	N	N	S1
20	N	N	S2	S2	N
21	N	N	S2	S2	N
22	N	N	S1	N	N
23	N	N	S2	S2	N
24	N	N	S2	S2	N
25	N	N	S1	S2	N
26	N	N	S1	N	N
27	N	N	S2	N	N
28	N	N	N	N	S1
29	N	N	S2	S2	N
30	N	N	S2	S2	N

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp - rice rotation crops, LUT 4: Shrimp crop, LUT 5: Rice - upland rotation crops

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable

Appendix 7. Land economic suitability in Fuzzy operator by Lukasiewicz

LU	Land suitability classification				
	LUT 1	**LUT 2**	**LUT 3**	**LUT4**	**LUT 5**
1	N2	N2	N2	N2	S3
2	N2	N2	N2	N1	N2
3	N2	N2	N2	N1	N2
4	N2	N2	S3	N1	N2
5	N2	N2	N2	N2	S3
6	S1	S1	N2	N2	S2
7	S1	S1	N2	N2	S2
8	S1	S1	N2	N2	S1
9	N2	N2	S1	N1	S3
10	N2	N2	S1	N1	N2
11	S1	S1	N2	N2	S2
12	N2	N2	S3	N1	N2
13	N2	N2	S3	N1	N2
14	N2	N2	S3	N1	N2
15	N2	N2	S1	N1	S3
16	N2	N2	S3	N1	N2
17	N2	N2	S1	N1	N2
18	N2	N2	S1	N1	N2
19	N2	N2	N2	N1	S3
20	N2	N2	S3	N1	N2
21	N2	N2	S3	N1	N2
22	N2	N2	S1	N1	N2
23	N2	N2	S3	N1	N2
24	N2	N2	S3	N1	N2
25	N2	N2	S1	N1	N2
26	N2	N2	S1	N1	N2
27	N2	N2	S3	N1	N2
28	N2	N2	N2	N1	S3
29	N2	N2	S3	N1	N2
30	N2	N2	S3	N1	N2

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp - rice rotation crops, LUT 4: Shrimp crop, LUT 5: Rice - upland rotation crops

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable

Appendix 8. Land sustainable suitability in Fuzzy operator by Lukasiewicz

	Land suitability classification				
LU	**LUT 1**	**LUT 2**	**LUT 3**	**LUT 4**	**LUT 5**
1	N	N	N	N	S1
2	N	N	N	S2	N
3	N	N	N	S1	N
4	N	N	S2	N	N
5	N	N	N	N	S1
6	S1	S1	N	N	S1
7	S1	S2	N	N	S1
8	S1	S1	N	N	S1
9	N	N	S1	N	S1
10	N	N	S1	N	N
11	S1	S2	N	N	S1
12	N	N	S2	S1	N
13	N	N	S2	S1	N
14	N	N	S2	S1	N
15	N	N	S1	N	S1
16	N	N	S2	S2	N
17	N	N	S1	S2	N
18	N	N	S1	N	N
19	N	N	N	N	S1
20	N	N	S2	S2	N
21	N	N	S2	S2	N
22	N	N	S1	N	N
23	N	N	S2	S2	N
24	N	N	S2	S2	N
25	N	N	S1	S2	N
26	N	N	S1	N	N
27	N	N	S2	N	N
28	N	N	N	N	S1
29	N	N	S2	S2	N
30	N	N	S2	S2	N

LUT 1: Three rice crops, LUT 2: Two rice crops, LUT 3: Shrimp - rice rotation crops, LUT 4: Shrimp crop, LUT 5: Rice - upland rotation crops

S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: None suitable