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Land-Use Optimization and Allocation for Saltwater Intrusion Regions: A Case Study in Soc Trang Province, Vietnam

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Abstract: Land-use planning plays an important role in agricultural development. However, the tools used to support planners in proposing land-use planning solutions are lacking, especially when considering saltwater intrusion conditions in coastal regions. In this study, optimization is applied by analyzing land use in developing solutions for agricultural land-use planning, wherein a multi-objective optimization model is developed to optimize land-use area, including land-use allocation, and taking into account socioeconomic and environmental factors. The model was applied to three districts of Soc Trang province, Vietnam (Long Phu, My Xuyen, and Tran De), representing three ecological regions of salt water, brackish water, and fresh water in the Mekong Delta of Vietnam. The results are shown for the implementation of two multi-objective optimization scenarios (in terms of profit, labor, environment benefits, and risk reduction) as follows: (i) multi-objective optimization of agricultural land use until 2030 under normal conditions; (ii) optimizing agricultural land use until 2030 under climate change conditions similar to the 2016 drought and saltwater intrusion phenomenon in the Mekong Delta. The results demonstrate that the second scenario is the preferred option for implementing land-use planning thanks to the balance between good profits and minimizing economic and environmental risk. Land allocation was carried out by taking into account the factors of household economics, the influence of adjacent production types, local traffic, and canal systems to allocate areas toward ensuring optimal land use. This process, involving a combination of land-use optimization and spatial allocation, can help planners to improve the quality of agricultural land-use planning.

Keywords: multi-objective optimization; land use; land-use allocation; saltwater intrusion; Mekong Delta; Soc Trang

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1. Introduction

The Mekong Delta is the largest food production region in Vietnam, accounting for 55.7% of Vietnam's rice output [1]. However, climate change and sea level rise are reported to have a significant influence on agricultural land usage [2,3]. People are still poor and vulnerable to climate change and sea level rise [2,4]. Many authors have evaluated the types of land use that can help in reducing risks under extreme weather or climate change, such as rice–shrimp cultivation in brackish coastal water areas [5] and rice–vegetable cultivation in freshwater ecological zones due to their ability to adapt to climate change in the context of freshwater scarcity caused by saline intrusion [6,7]. However, the area used for rice–shrimp cultivation is decreasing because of farmers pursuing profits by converting it to that used for shrimp cultivation without paying attention to the environment [8] and, at the same time, due to rice–vegetable cultivation facing difficulties in determining growing areas and difficulties related to financial capacity [9]. This presents managers with the challenge of developing profitable agricultural land-use options while minimizing costs, hazards, and environmental impact.

For agricultural land-use planning, plans are developed based on FAO's guiding process [10] in which land suitability evaluation methods are used to select suitable agricultural land-use types and determine the regions suitable for land units [11]. Then, an alternative assessment of socioeconomics to optimize land-use options becomes necessary [12], but there is still a lack of tools to support planners in developing countries [13].

Furthermore, the linear programming method has been used with GIS to optimize land use toward maximizing profits within the constraints of capital, labor, production, and ecological restrictions [14,15]. Multi-objective optimization studies, such as cost minimization combined with the maximum area of usage [16], are used in a multi-objective environment. Alternatively, a combination of LULC prediction and allocation are used to minimize surface runoff for flood mitigation under dry, normal, and wet years to increase environmental benefits [17]. To compute the optimal area of dominating uses across the entire research region, some studies employed linear maximization or neuron networks [18].

In recent related optimality studies in the Mekong Delta, optimization approaches have been used with land units as a basis [11]. In particular, appropriate optimal objectives, such as maximizing profits, labor, costs, capital use efficiency, and land suitability, have been established on each land unit [19,20]. The advantage of these studies is to propose optimal areas for agricultural land-use types (LUTs) based on socioeconomic and environmental constraints and on the characteristics of each land unit rather than the entire area. In these studies, however, land-use allocation tools used to help users to arrange land-use types on the map were lacking. In addition, establishing mathematical models is challenging for managers who have no background in informatics.

Regarding land-use allocation, many land-use allocation methods have been used including full land-unit allocation [19,20], pixel-based allocation using models (CLUE-S [21], CLUMondo), and Cellular Automata (CA) analysis [22]. Many studies used the CLUE-S model to distribute land layout, in which the optimized area of land-use types is the required input for CLUE-S [17,18,23] or CLUMondo [24]. Some studies have used separate models to solve the problem of spatial arrangement of urban land use while taking infrastructure into account.

The previous optimization studies have helped planners to make economic-based land-use decisions. However, the question is how to build a model to optimize land-use areas for areas affected by climate change events such as drought and saltwater intrusion. In implementing land-use types, the integration of qualitative factors affecting land-use types, such as risk level and local investment priority policies, also needs to be considered in optimization and land allocation. Therefore, it is necessary to conduct research to propose a scientifically based optimization model for developing agricultural land-use plans, with goals that consider a combination of economic, social, and political factors; policies; and the environment for the purpose of increasing farmers' incomes. Three districts of Soc Trang province in the Mekong Delta region are selected as the study area to build a model that provides tools that support planners in developing agricultural land-use solutions with suitable conditions, socioeconomic constraints, and saltwater intrusion situation, thereby minimizing risks upon implementation for sustainable development.

2. Materials and Methods

2.1. Study Area

Soc Trang province is located in the Mekong Delta at the southern mouth of the Hau River about 60 km from Can Tho. It shares borders with Hau Giang, Tra Vinh, Bac Lieu, and the East Sea. Soc Trang province has 11 administrative units in 2023, including Soc Trang city, Vinh Chau town, Nga Nam town, and eight districts (Ke Sach, My Tu, Cu Lao Dung, Long Phu, My Xuyen, Thanh Tri, Chau Thanh, and Tran De). The study area was chosen based on having contiguous districts with the ecological characteristics of fresh, brackish, and saline water. This helps with the mapping of specific land uses for these ecoregions.

The study area consists of three districts in Soc Trang province, which were chosen based on the aforementioned criteria and are as follows: My Xuyen, Long Phu, and Tran

De (Figure 1). Long Phu, in particular, is in a freshwater area but is vulnerable to saline intrusion during extreme weather events (such as drought and saline intrusion in 2016); My Xuyen is in a brackish water region; and Tran De is divided into two areas of the saline area outside the dike systems at the river's mouth and the freshwater area inside the dike systems.

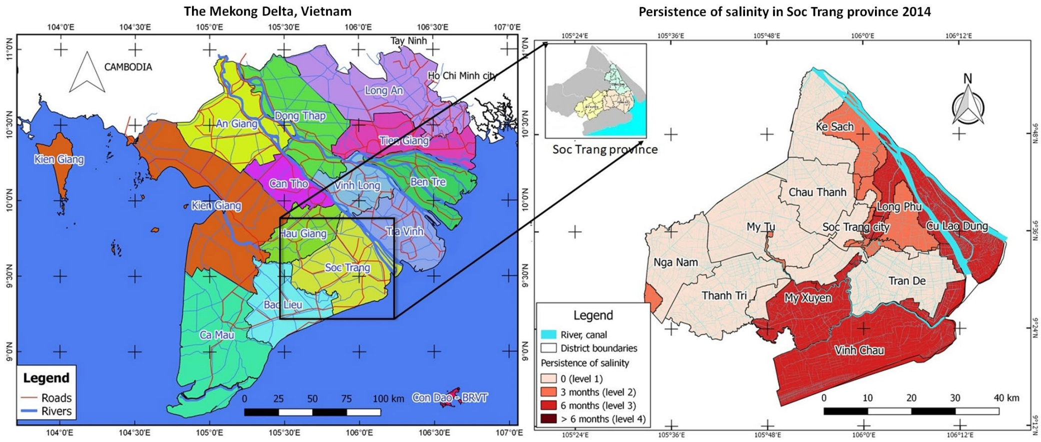


Figure 1. The study area in Soc Trang province, Vietnam.

Soc Trang is located in a tropical climate zone influenced by the monsoon. The year-round climate throughout the province has two distinct seasons of the dry season and the rainy season. The rainy season occurs from May to October with an average annual rainfall of 1864 mm, and the dry season is from November to April of the following year. Therefore, during the dry season, coastal districts are impacted by saline intrusion, which leads to special requirements for diverse land uses according to climatic and hydrological characteristics and poses challenges for the study area regarding agricultural land-use planning for the future.

The statistics from 2010 to 2018 of all three districts, as shown below, are used to analyze changes in the area of rice cultivation over time as a basis for predicting the area used for specialized cultivation, fruit trees, and aquaculture, as illustrated in Figure 2. Specifically, the cultivated area of the districts is focused solely on producing two rice crops, and cultivation of the summer–autumn crop spans a large area. The data show the total area of rice cultivated each year.

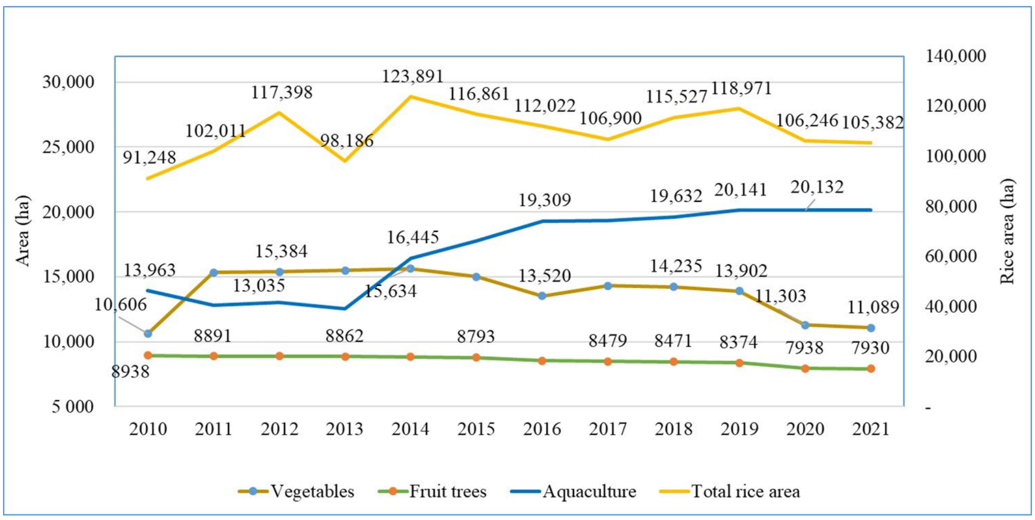


Figure 2. Cultivated agricultural land-use area of the three districts from 2010 to 2021.

Figure 2 also depicts the cultivated area of vegetables, fruit trees, and aquaculture in the districts of Long Phu, Tran De, and My Xuyen from 2010 to 2021. In general, the area of vegetables and crops has fluctuated, but there has been a consistent increase in recent years. In contrast, the area of fruit trees varies the least, ranging from 8546 ha to 8938 ha. From 2010 to 2021, the aquaculture sector, in particular, grew steadily.

2.2. Data Collection

Based on the research of Lambin and Geist [25] and previous studies, including those in Vietnam, the factors influencing land-use type selection were chosen from similar studies in the Mekong Delta, Vietnam, as shown in Table 1. Economic variables such as profit and market demand are the elements influencing the area of relevant land-use types. The components of investment capital and household capital indicate whether or not the household has the ability to arrange various types of land use. Many studies have examined how social factors like labor, educational level, and infrastructure issues influence land use. To examine the possibility of selecting land use, the natural conditions of soil, water, environmental benefit, and risk of land use were surveyed.

Table 1. Socioeconomic factors related to land use.

Factor Group	Factors	Source
Economic	Profit	Santiphop et al. [26]; Liu and Xia [27]; Le et al. [28]; Pham et al. [29]
	Capital, cost	Le et al. [28]; Sofi et al. [30]
	Household capital	Bui et al. [31];
	Market demands	Santiphop et al. [26]; Liu and Xia [27]
Social	Labor	Pham et al. [29]; Sofi et al. [30]
	Educational level	Bui et al. [31];
	Neighborhood effect	Le et al. [32];
	Infrastructure (road, canals)	Le et al. [28]; Liu and Xia [27]
Environment	Risk of land use	Nghi and Hien [33]; Pham et al. [29]
	Natural factors: soil, water	Most related research

The number of agricultural households in the three districts in the study area is about 55,000. The total number of interview samples of agricultural production households in the three districts in the case study was selected based on Yamane's study (1967) [34], with a sampling error of 6% for seven land-use types with a total of 315 households (rounded up to 45 households per land-use type) distributed in three districts.

Individual interviews were conducted with experienced local farmers who had at least 10 years of farming experience in the study area. The questionnaire was designed using close-ended questions to collect data on household characteristics related to profitability, total cost, profits, labor demand (working days per year), environmental benefits, and the risk of LUTs for each land-use type (LUT). People evaluated that their LUT had a positive impact on improving the quality of the environment, and the risks of LUT were divided into four levels (high, medium, low, and no risk) corresponding to the percentage of farmers self-assessing the level of risk in agriculture production. The collected data were encoded and analyzed with descriptive statistics using the data source of the optimization model stored in Microsoft Excel software as the input.

In addition, details of the maps of soil types, depth of alum formation, water salinity, and duration of water salinity in 2015 were obtained from the Department of Agriculture and Rural Development of Soc Trang province for performing the land evaluation. The land-use map of the study area in 2015 as well as the saline intrusion maps in 2010 and 2015 were analyzed using data from the Department of Natural Resources and Environment.

2.3. Land-Use Optimization and Allocation

The mathematical model is built up of three blocks, as shown in Figure 3, in which the first section specifies the input data source, which includes economic, social, and environmental data; the second block contains the module for optimizing agricultural land area (land optimization module); and the third block contains the module for spatial allocation for land-use types (land allocation module).

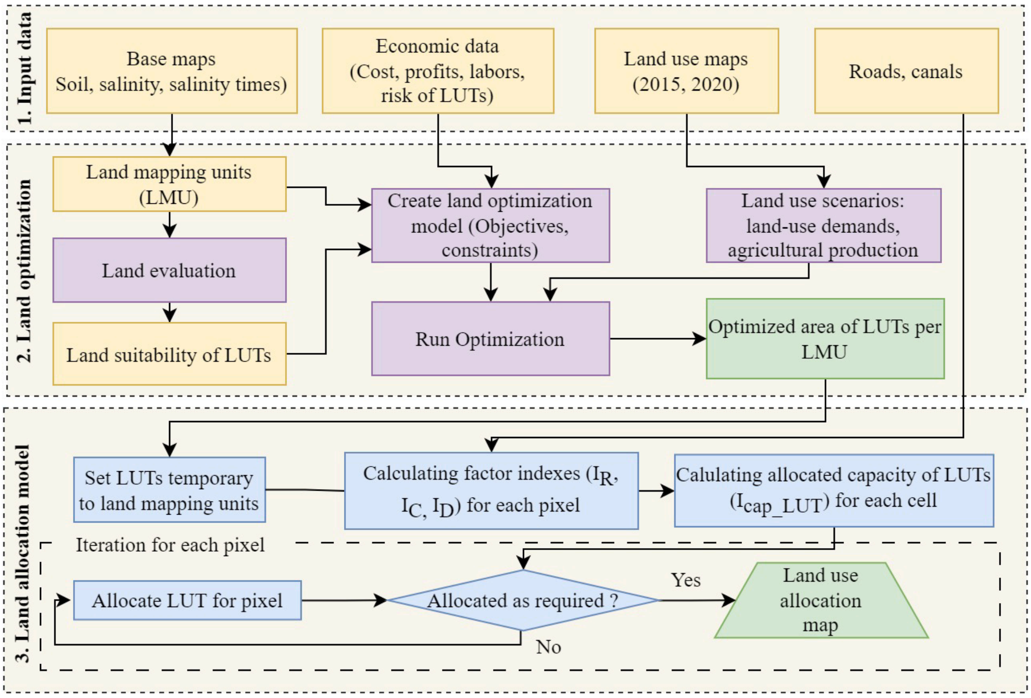


Figure 3. Research method.

The input data sources for the model include socioeconomic and spatial data, in which socioeconomic data contains information gathered during the economic research of land-use types, such as costs, profits, working days, and people's perceptions of the environmental advantages and risks of land use. Base map layers (such as soil, acid sulfate, salinity, and freshwater supply layers) are included in spatial data. To build a land unit map, these maps were overlaid using the Union method according to the FAO [11]. Other types of spatial data include infrastructure map layers for analyzing appropriate locations of use types (roads, canals).

For land-use area optimization in block 2 (Figure 3), the linear programing method is employed to determine the area of use types in each land unit with the best objective function for profit maximization or multi-objective optimization. This module was created using the Visual Basic.NET programming language and the LPSolve API function [35] (The program's code is provided in the Supplementary Materials section). Section 2.3.1 defines the objective function and constraint equations in detail. This module produces a CSV file that describes the optimized area of each land-use type for each land unit.

The land allocation step is presented in block 3 of Figure 3. This step is built according to the grid layout method of GAMA platform software version 1.8 [36] in which the output area of the optimized step is used as the land-use requirement condition of this module. The procedure for allocating the required area of each land unit is summarized as follows: First, a temporary land-use type is assigned to the cells within the same land unit. For a land unit allocated for only one land-use type, land arrangement is complete. For land units allocated for multiple uses, all of the cells are temporarily allocated with a non-priority land-use type as a base map in this step (which means the allocated area exceeds the requirement). These cells are noted with the label being unallocated. Next, each unallocated cell is calculated using the appropriate indices for the land-use types, including LUT density, distance to canal (I_C), distance to traffic (I_D), and the ability to arrange each LUT (I_{cap_LUT}). This iterative process is continued for each land-use type to sort cells through the descending order of I_{cap_LUT} and to set the land-use types for these cells. The output of the integrated system is a map of land-use options arranged according to the required area and with the appropriate spatial location set according to the requirements of the type of use.

2.3.1. Optimization Objective Functions

The function of maximum land suitability (Equation (1)), profit maximization (Equation (2)), and maximum linear objectives of the number of units of local labor used, the environmental benefit rate, and minimizing risk (Equation (3)) are set as the options to optimize the area of land-use types for each land unit in this study.

$$\max : \sum_{i=1}^{n}\sum_{j=1}^{m} S_{ij}X_{ij} \tag{1}$$

$$\max : \sum_{i=1}^{n}\sum_{j=1}^{m} P_{ij}S_{ij}X_{ij} \tag{2}$$

$$\max : w1\sum_{i=1}^{n}\sum_{j=1}^{m} P_{ij}S_{ij}X_{ij} + w2\sum_{i=1}^{n}\sum_{j=1}^{m} E_jX_{ij} + w3\sum_{i=1}^{n}\sum_{j=1}^{m} L_jX_{ij} - w4\sum_{i=1}^{n}\sum_{j=1}^{m} R_jX_{ij} \tag{3}$$

where the values are as follows:

$i \in [1, n]$, and n is the number of land mapping units; $j \in [1, m]$, and m is the number of LUTs.
X_{ij}: area of LUT_j in land unit i. P_{ij}: profit of LUT_j in land mapping unit i (unit: million VND/ha).
S_{ij}: land suitability of LUT_j in land unit i (values).
L_j: the number of working days of LUT_j per hectare.
E_j: environmental benefit coefficient of LUT_j, which is the farmer's assessment of the environmental benefits of LUTs.
R_j: risk coefficient of LUT_j, which is the LUT_j productivity risk indicator. The smaller the risk value is the greater the contribution to the goal function.
W_i: the weight of the objectives. In this study, the assumption of equal-weighted goals is set to 1 by default with the meaning that the goals in the multi-objective function have the same priority, and these weights can be adjusted (from 0 to 1) depending on the priority of the local goals for local development orientation.

2.3.2. Constraint Equations

The objective function is constrained by a set of equations that includes the area of land units, the total number of working days, the total production, or the minimum and maximum area of LUTs.

For each land mapping unit (LMU), the total area of the LUT within the LMU should be less than the area of the LMU, $i \in [1, n]$ (Formula (4)):

$$\sum_{i=1}^{i=1}\sum_{j=1}^{j=1} X_{ij} \le \text{AreaofLMU}_i \tag{4}$$

The total labor demand of the LUTs cannot exceed the local agricultural labor resources (Formula 5).

$$\sum_{i=1}^{n}\sum_{j=1}^{m} L_jX_{ij} \le \text{totalworkingdays} \tag{5}$$

The minimum of each agricultural product to supply (Formula (6)).

$$\sum_{i=1}^{n}\sum_{j=1}^{j=1} Y_jX_{ij} \ge \text{minimumproductionofLUT}_k \tag{6}$$

Y_j: yield of LUTs that provide the product k, $k \in [1, p](\text{numberofproducts})$.

The maximum of each agricultural product to supply (Formula (7)).

$$\sum_{i=1}^{n}\sum_{j=1}^{m} Y_j X_{ij} \leq \text{maximumproductionofLUT}_k \quad (7)$$

Total area of $LUT_j \leq$ total limited area of LUT_j (Formula (8))

$$\sum_{i=1}^{n}\sum_{j=1}^{m} X_{ij} \leq \text{limitedareaofLUT}_j \quad (8)$$

2.3.3. Land-Use Allocation

After determining the optimal area of each land-use type (LUT) per land unit, we proposed the detailed land-use allocation within each land unit. In particular, land-use types are arranged into the cells inside a land unit map through the cellular automata method and multi-criteria assessment based on natural, socioeconomic, and environment factors.

The allocation capability index for a LUT of a pixel $I_{cap\_LUT}(i)$ was determined using Formula (9). A LUT was assigned to a cell when it had the highest value of I_{cap_LUT}. In case there were many LUTs with the same value of I_{cap_LUT}, the LUT was randomly selected from these LUTs.

$$I_{cap\_LUT}(i) = \frac{(W_R I_R + W_C I_C + W_D I_D(i) + W_I I_I)}{W_R + W_C + W_D + W_I} \quad (9)$$

where the distance index from a cell to the nearest road (I_R) and canal (I_C) is calculated through the shortest distance from the position of each cell to the nearest road (canal). Distance values were also normalized to the range of [0, 1] (Equations (10) and (11)).

$$I_R = 1 - \frac{\text{distance(cell, nearest\_road)}}{\text{max\_distance\_cell\_road}} \quad (10)$$

$$I_C = 1 - \frac{\text{distance(cell, nearest\_canal)}}{\text{max\_distance\_cell\_canal}} \quad (11)$$

The density of land-use type in the neighborhood of a cell (I_D) is determined by counting the number of neighborhood cells of each land-use type divided by 8.

$$I_D(i) = \frac{\text{Number\_neighborb\_cells\_in\_LUTi}}{8} \quad (12)$$

The investment priority index (I_I) represents the pixel located in the municipalities with a high priority for investment, which included the commune groups assigned values for this index. The communes are divided into three groups based on their level of achievement of the new rural construction standards (NRSs) in Vietnam; the commune group is then standardized into three values [1; 0.5; 0].

W_R, W_C, W_D, and W_I in Equation (9) are the weights for I_R, I_C, I_D, and I_I. By default, these weights are set to 1. In the application scenario, the weights were modified by experimenting with different weight combinations in the layout and comparing the results with the historical map.

3. Results

3.1. Analysis of Economic Factors Affecting Agricultural Land Use

3.1.1. Dominant Agricultural Land-Use Types

The agricultural land-use types (LUTs) chosen for research in this study include those employed for freshwater, brackish, and saline ecological zones where the LUTs were chosen based on land-use dominance in the Mekong Delta region. Prospective LUTs in the three districts include those for three rice crops, two rice crops, rice–vegetables (two rice and one vegetable crop), rice–shrimp, annual crops (two to three vegetable crops), fruit trees, and shrimp.

3.1.2. Socioeconomic and Environmental Factors

A huge difference in profits can be seen in Table 2, especially between LUT7 (VND 277.23 million) and LUT2 (only about VND 42.42 million). However, in order to be able to implement LUT7, it is necessary to have not only capital but also intensive farming techniques as well as suitable natural conditions.

Table 2. Socioeconomic and environmental factors of LUTs.

LUT		**Labor Demand**	**Profits**	**Environmental Benefits**	**Risk in Cultivation**
		(Day/Year/ha)	**(Million VND/ha)**		
LUT1	Three rice crops	92	58.48 ± 4.78	3.27 ± 1.18	3.20 ± 1.19
LUT2	Two rice crops	78	42.42 ± 4.13	3.96 ± 1.26	2.62 ± 0.68
LUT3	Rice–vegetable	121	80.27 ± 4.96	4.02 ± 1	2.51 ± 0.81
LUT4	Rice–shrimp	86	86.62 ± 7.02	4.22 ± 0.87	2.96 ± 0.92
LUT5	Annual crops	233	88.07 ± 5.59	3.18 ± 1.18	3.36 ± 1.01
LUT6	Fruit trees	115	184.00 ± 34.83	3.42 ± 1.06	3.62 ± 0.85
LUT7	Shrimp	217	277.23 ± 30.16	3.16 ± 1.01	4.24 ± 1.08

The results of the survey include the number of labor days for each agricultural land-use type per year, with vegetables needing the highest number of working days followed by shrimp, which farmers have to take care of all year. Two rice–vegetable and fruit crops have the same number of working days, equivalent to 115 and 121 days per hectare per year, respectively.

The data for risk factors include details about perceived uncertainty in yields, prices, and weather risks. Table 2 shows that people rate the riskiest form of land-use type as that for shrimp farming, with a score of 4.24 out of 5.0 for production. In contrast, most people think that land-use types for two rice and rice–vegetable crops are low-risk or no-risk forms of crop cultivation, with scores of 2.62 and 2.51, respectively. In the case of fruits and vegetables, the risk is assessed to be quite high (3.36 and 3.62) as farming is market-dependent, and yield and weather generally do not affect these LUTs.

In terms of the environment, the analysis results show that land use-types for two rice, rice–vegetable, and rice–shrimp farming are environmentally beneficial ones, with evaluated scores of 4.22, 4.02, and 3.96, respectively. LUTs for shrimp, annual crops, and three rice crops, on the other hand, were rated as being bad for the environment (with scores of 3.16, 3.18, and 3.27, respectively). Of the LUTs, those for upland crops and shrimp showed the highest rates of negative environmental impact, among which that for fruit trees only received 3.42 points. The outcomes of these assessments will be normalized and the respective values used as variables of the LUTs.

In Vietnam, the criteria for classifying the new rural commune standard include many significant variables such as household income, commune poverty rate—which can be used to reflect commune investment level—and household investment aptitude. The results of establishing new rural communes (NRCs) were used to assign investment ability indicators as a qualitative element influencing agricultural land-use allocation. The investment ability of communes was classified into three groups based on their revenue and poverty rates as follows: Group 1 consisted of communes that met NRC standards; Group 2 consisted of communes that did not reach NRC standards but have a per capita income of VND 20–28 million and a poverty rate of less than 6%; and Group 3 consists of the other communes (Table 3).

Table 3. Communes organized into groups based on economic potential.

District	Communes		
	Group 1	**Group 2**	**Group 3**
Long Phu	Truong Khanh, Tan Thanh,	Long Phu, Song Phung, Hau Thanh	Long Duc, Chau Khanh, Tân Hung, Phu Huu
Tran De	Trung Binh, Lich Hoi Thuong, Thanh Thoi Thuan, Vien Binh	Vien An	Dai An 2, Lieu Tu, Tai Van, Thanh Thoi An
My Xuyen	Hoa Tu 1, Hoa Tu 2, Ngoc To, Đại Tâm, TT My Xuyen	Ngoc Dong, Gia Hoa 1, Gia Hoa 2	Tham Don, Thanh Phu, Thanh Quoi
Household's income per year	NRC qualified (greater than VND 30 million)	Not up to NRC standard (VND 20–28 million)	Not up to the NRC standard (<VND 20 million)
Poverty rate	NRC qualified ≤4%	NRC qualified (≤6%)	Not up to the NRC standard NRC (≤23%)

According to the survey results, local agricultural production was experiencing issues such as (i) water supply and drainage issues due to distance from canals, (ii) difficulty in transporting materials and traveling due to narrow or unpaved roads, and (iii) saline leakage from shrimp ponds into rice fields affecting farming practices. Apart from natural factors such as land and water, individuals still encountered difficulties in manufacturing owing to a lack of energy or poor equipment functioning, thereby impacting production efficiency.

Figure 4 shows that the three LUTs influenced by neighboring land use are those for two rice crops, three rice crops, and rice–shrimp. If nearby homes raise shrimp or keep salt water in the pond, the neighboring rice-growing households will be unable to cultivate rice or will obtain low yields. The most important priority for shrimp and fruit farming was a strong electric power source to operate machinery, followed by the need to be positioned near a road and the effect of neighboring LUTs. In reality, if people wish to cultivate aquaculture items, the nearby homes must also cultivate them in the same manner, resulting in great efficiency. Approximately 20% of respondents agreed that vegetables and fruits should be grown near rivers and canals. However, due to the agricultural practices of farmers, vegetables and fruit have to be positioned near roads.

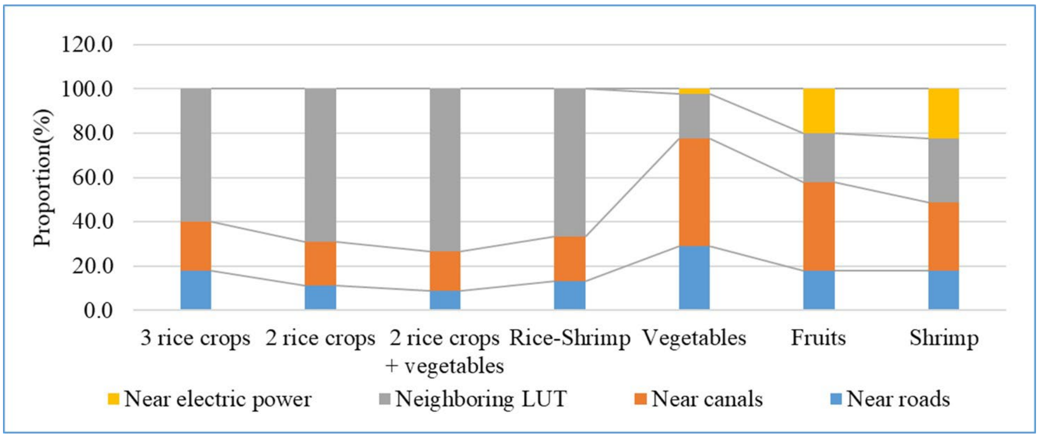


Figure 4. Infrastructure requirements of LUTs.

Based on the specific socioeconomic characteristics in previous studies that had varying effects on land-use selection, the factors have been graded, as shown in Table 4, and separated into two groups as follows: the group of factors influencing land-use type selection and the group of factors influencing spatial layout. Each element was thought to serve only the functions of optimizing land use and allocating agricultural land use.

Table 4. A summary of the factors influencing agricultural land use.

Factors	Detailed	Impact on LUTs and Allocation Orders	Applied
Economic	Profit	LUT7, LUT6, LUT5, LUT4, LUT3, LUT1, LUT2.	Optimization
	Capacity of investment	LUT7, LUT6, LUT5, LUT4, LUT3, LUT1, LUT2	Allocation
Social	Labor days	LUT5, LUT7, LUT3, LUT6, LUT1, LUT4, LUT2	Optimization
	Road systems	LUT5, LUT6, LUT7, LUT1, LUT4, LUT3, LUT2	Allocation
	Channel systems	LUT5, LUT6, LUT7, LUT4, LUT3, LUT1, LUT2	Allocation
	Neighboring LUT	LUT7, LUT4, LUT1, LUT3, LUT2	Allocation
Environment	Land suitability	Based on Land suitability order	Optimization
	Risk of LUT	LUT7, LUT6, LUT1, LUT5, LUT4, LUT3, LUT2	Optimization
	Benefit of environment	LUT2, LUT4, LUT3, LUT1, LUT6, LUT5, LUT7	Optimization

Factors such as land suitability, profitability, number of labor days, risk level, and environmental benefit were employed in the optimization module. These elements were classified as either single-target or aggregated socioeconomic goals.

Factors influencing agricultural land-use allocation include investment capacity, transportation infrastructure, canals, and the needs of the surrounding LUTs. The LUTs were ordered according to the survey results, which were assessed and taken into account in the land layout. When compared with other land-use types, the combined data reveal that LUT 7 (shrimp) and LUT 6 (fruit trees) were prioritized for locations near roads, canals, and rivers, where investment is viable. This functionality was found for two locations as follows: Brackish areas prioritized for shrimp were arranged in priority places near roads, canals, and rivers, and in areas with investment potential. These places gradually moved outwards and were followed by rice–shrimp arrangements. Vegetables and fruit trees were prioritized for planting near watery bodies.

3.2. Application of Integrated Systems in Soc Trang Province

3.2.1. Land Evaluation

Land mapping unit (LMU) maps were created by utilizing the Union technique to analyze maps according to attributes such as soil, depth to the occurrence of acid sulfate soil (ASS), water salinity, and water salinity duration for three districts in Soc Trang province (Long Phu, Tran De, and My Xuyen). The districts' LMU map was divided into 28 LMUs as in Figure 5.

Table 5 shows the detailed attributes of the units in which unit 14 has the largest land area (18,586.90 ha) in My Xuyen district, with soil characteristics of Fluvisol soil type, an acid sulfate soil layer depth of less than 50 cm, 8–12‰ salinity, and a salinity period of 6 months each year. There are two large-scale land units in Tran De district as follows: unit 3 and unit 6, which have areas of 16,996.50 ha and 10,047.49 ha, respectively. These are low salinity land units since they are located inside of the dike and are supplied with fresh water through the canal system, but there is only sufficient irrigation capacity to cover the needs of two crops.

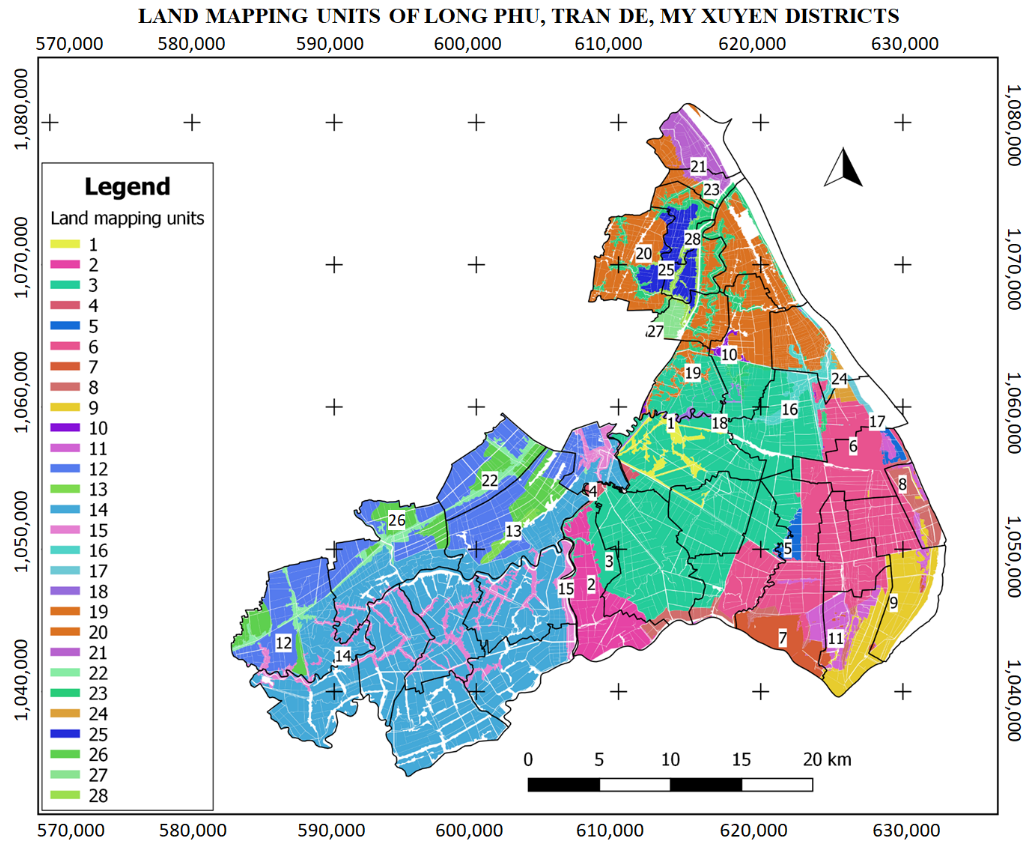


Figure 5. Land mapping units of the study area.

Table 5. Land suitability of land mapping units.

LMU	Soil Type	Acid Sulfate Occurred	Salinity (‰)	Persistence of Salinity (Months)	Irrigation Capability (Months)	LUT1	LUT2	LUT3	LUT4	LUT5	LUT6	LUT7
1	Anthrosol	No	2–4	5	7	0	0	0	0	0.33	1	0
2	Fluvisol	Active at <50 cm	2–4	6	6	0	0.67	0.67	0	0.33	0	0
3	Fluvisol	Active at >50 cm	2–4	5	7	0	0.67	0.67	0	0.67	0	0
4	Anthrosol	No	4–6	5	7	0	0	0	0.67	0	0	0.33
5	Arenosol	No	4–6	6	6	0	0.33	0.33	0	0.67	0.67	0
6	Fluvisol	Active at <50 cm	4–6	5	7	0	1	0.67	0	0.67	0.33	0
7	Anthrosol	Active at >50 cm	12–20	12	0	0	0	0	0.33	0	0	0.67
8	Fluvisol	No	12–20	12	0	0	0	0	0.33	0	0	0.67
9	Fluvisol	Active at <50 cm	12–20	12	0	0	0	0	0.67	0	0	1
10	Fluvisol	Active at <50 cm	2–4	3	9	0	0.67	0.33	0	0.33	0.67	0
11	Anthrosol	Active at >50 cm	4–6	5	7	0	0.67	0.33	0	0.67	0	0
12	Fluvisol	No	6–8	3	9	0	1	0.67	0	0.67	0.33	0
13	Arenosol	No	2–4	3	9	0	0.33	0	0	1	0.67	0
14	Fluvisol	Potential at <50 cm	8–12	6	6	0	0	0	1	0.33	0	0.33
15	Anthrosol	Potential at >50 cm	6–8	6	6	0	0	0	0	0.67	1	0
16	Anthrosol	Potential at >50 cm	2–4	3	9	0	0.33	0.33	0	0.67	1	0
17	Fluvisol	Active at <50 cm	8–10	6	6	0	0	0	0	0.67	0.33	0.67
18	Anthrosol	Potential at >50 cm	<2	5	7	0	0	0	0	1	0.33	0
19	Anthrosol	Potential at >50 cm	<2	3	9	0	0	0	0	1	0.33	0
20	Fluvisol	No	2–4	3	9	1	0.67	0.67	0	0.67	1	0
21	Fluvisol	No	2–4	6	6	0.33	0.67	0.67	0	0.67	1	0
22	Anthrosol	Potential at >50 cm	2–4	5	7	0	0	0	0	0.67	1	0
23	Anthrosol	No	2–4	2	10	0	0	0	0	0.67	1	0
24	Arenosol	No	8–10	5	7	0	0	0	0	0.67	0.67	0.33
25	Fluvisol	Active at >50 cm	2–4	6	6	0.67	0.67	1	0	0.67	0	0
26	Fluvisol	Potential at <50 cm	6–8	6	6	0	0.67	0.67	0	0.33	0.33	0
27	Fluvisol	No	6–8	3	9	0.67	0.67	0.67	0	0.67	0.67	0
28	Anthrosol	Active at >50 cm	2–4	3	9	0	0	0	0	0.67	1	0

Notes: 1: highly suitable, 0.67: moderately suitable, 0.33: marginally suitable, 0: non-suitable.

In addition, the results of the adaptive classification of 7 land-use types across 28 land units are also shown in Table 5. The FAO (1976) adaptation levels are classified according to the levels of S1, S2, S3, and N, which correspond to the values of highly suitable, moderately suitable, marginally suitable, and non-suitable. These values are normalized to 1, 0.67, 0.33, and 0 for the optimization model.

3.2.2. Configuring Optimization Scenarios

The optimization scenarios were set to optimize the agricultural land area of the three districts until 2030 with socioeconomic and environmental changes.

Scenario 1: Optimizing agricultural land until 2030 under normal conditions. This scenario was designed to determine the optimal land area and land allocation for agricultural production under actual natural conditions and socioeconomic development until 2030.

Scenario 2: Optimizing agricultural land until 2030 under conditions of environmental and climate change events similar to the drought and salinity intrusion phenomena in 2016 and 2020 in the Mekong Delta. It was recommended by authorities that farmers reduce three-rice-crop areas. Thus, the intention of this scenario is to explain when it is recommended to not use a three-rice-crop area as before and which LUT is necessary to replace it.

For each scenario, three alternative options were analyzed as follows: that of optimizing land suitability level, that of optimizing profits, and that of optimizing multiple objectives (profits, labor, risks, and environmental benefit). Regarding the limited areas of the LUTs in the scenarios, the minimum and maximum thresholds of the LUT areas are defined in Table 6. In the optimization model, the value of unlimited is represented by a constant number (1,000,000 ha) that is larger than the study area.

Table 6. Restricted area of the LUTs in the two scenarios.

LUT	Scenario 1		Scenario 2	
	Lower Bound (ha)	**Upper Bound (ha)**	**Lower Bound (ha)**	**Upper Bound (ha)**
LUT1	0	Unlimited	0	Unlimited
LUT2	0	Unlimited	0	Unlimited
LUT3	0	12,768	0	15,436
LUT4	0	Unlimited	0	Unlimited
LUT5	0	2100	0	2500
LUT6	0	8799	0	8936
LUT7	0	16,697	0	19,236

3.2.3. Exploring Weights of the Multi-Objective Land Optimization Module

In the two scenarios, the weight of the objectives was set to 1 by default, which indicates that the weights are equal. The land optimization module provides functionality that allows users to automatically search for target weights based on historical land use, with each set of target weights showing the total area of each land-use type for comparison with the statistical area. From there, the appropriate set of weights for the local objectives is determined.

The objective parameters of the optimization were explored by combining three target parameters (W_1, W_2, and W_3) in which the profit parameter (W_1) ranges from 0.1 to 0.8 and W_2 from 0.1 to 0.9, with W_1 and W_3 being the compensation for the two first parameters. The explored result of 36 sets of parameters led to the weights W_1 = 0.4, W_2 = 0.2, and W_3 = 0.4 being selected to develop multi-objective agricultural land-use optimization for the two scenarios.

3.2.4. Optimizing Agricultural Land-Use Area

Figure 6 depicts the results of the optimization of the area of LUTs under Scenario 1 in which the land-use distribution maps of the three options were analyzed, including adaptation level optimization (Figure 6a), optimal profit maximization (Figure 6b), and optimization of the combined socioeconomic and environmental goals (Figure 6c). In such cases, the map of Option 1 (Figure 6a) differs significantly from the other two options (Figure 6b,c), which are mostly represented by the amount of rice–crop land and shrimp farming land. The distribution of crop rice in Option 1 is concentrated in the northern part of Long Phu district, while for the other two options, the area of rice crop land is arranged further along the road in Tran De district. For shrimp farming land, the maps of Options 2 and 3 both show the same arrangement in My Xuyen districts (western part of the maps).

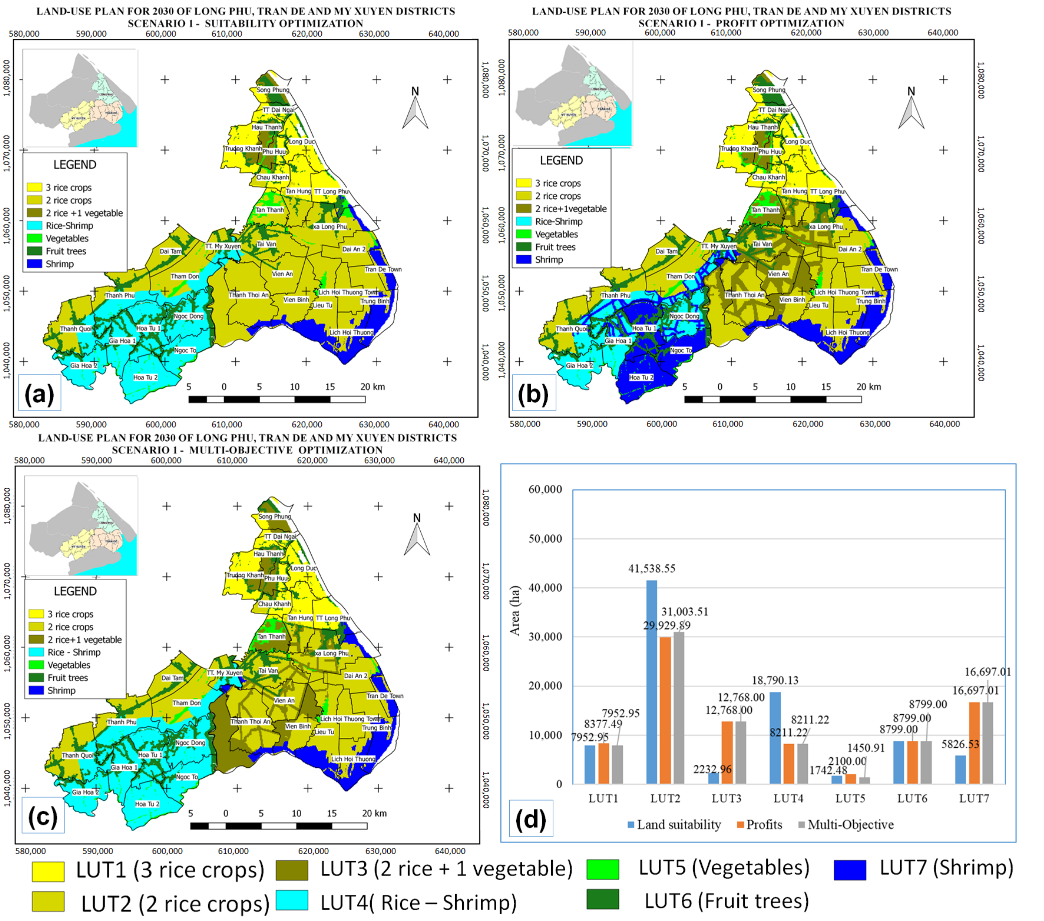


Figure 6. Land-use maps of three alternatives in Scenario 1. (**a**) Option 1: maximization of land suitability, (**b**) Option 2: maximization of profits, (**c**) Option 3: maximization of multiple objectives, (**d**) land-use area of the three alternative options.

A more extensive analysis of the area of Scenario 1 (Figure 6d) reveals that three land-use types for rice crops (LUT1) and fruit trees (LUT6) have comparable distribution areas due to the area requirements of the three alternatives. However, the area of the two rice crops (LUT2) and rice–shrimp (LUT4) in Option 1 exceeds that of the other two options, totaling more than 10,000 hectares for each type due to the high land suitability but poorly lucrative use patterns. In contrast, the amount of rice–crop land (LUT3) is less than 10,000 ha smaller than the other two alternatives due to limited adaptability but offers high profit. The remaining land-use types of the two alternatives have similar areas, although the size of LUT2 and LUT5 of Option 1 is 400 ha and 550 ha larger, respectively, than that of Option 2. Regarding LUT2, the analysis shows Option 1 is superior to Option 2. The results reveal that Option 3 has several advantages in terms of the environment and risk limits of Option 1 as well as the profit advantages of Option 2.

For Scenario 2, under the conditions of environmental changes due to climate change, the analysis results for the three land-use options in 2030 are shown in Figure 7. Regarding the maps of the three alternatives, the map in Figure 7a gives similar results to Figure 6a and demonstrates a difference compared with the other two options (Figure 7b,c). The remaining two optimization options show that the layout of shrimp land is similar in both. However, the area and arrangement of rice–crop land (LUT3) differ. Option 2 focuses on arranging rice–vegetable crops in Tran De district while Option 3 focuses on arranging this type in Long Phu district. The reason for the different spatial arrangement of LUT 3, despite having the same required area, is because there are a higher number of land units for the two-rice-crop land of Option 3 and less area for growing vegetables than in Option 2.

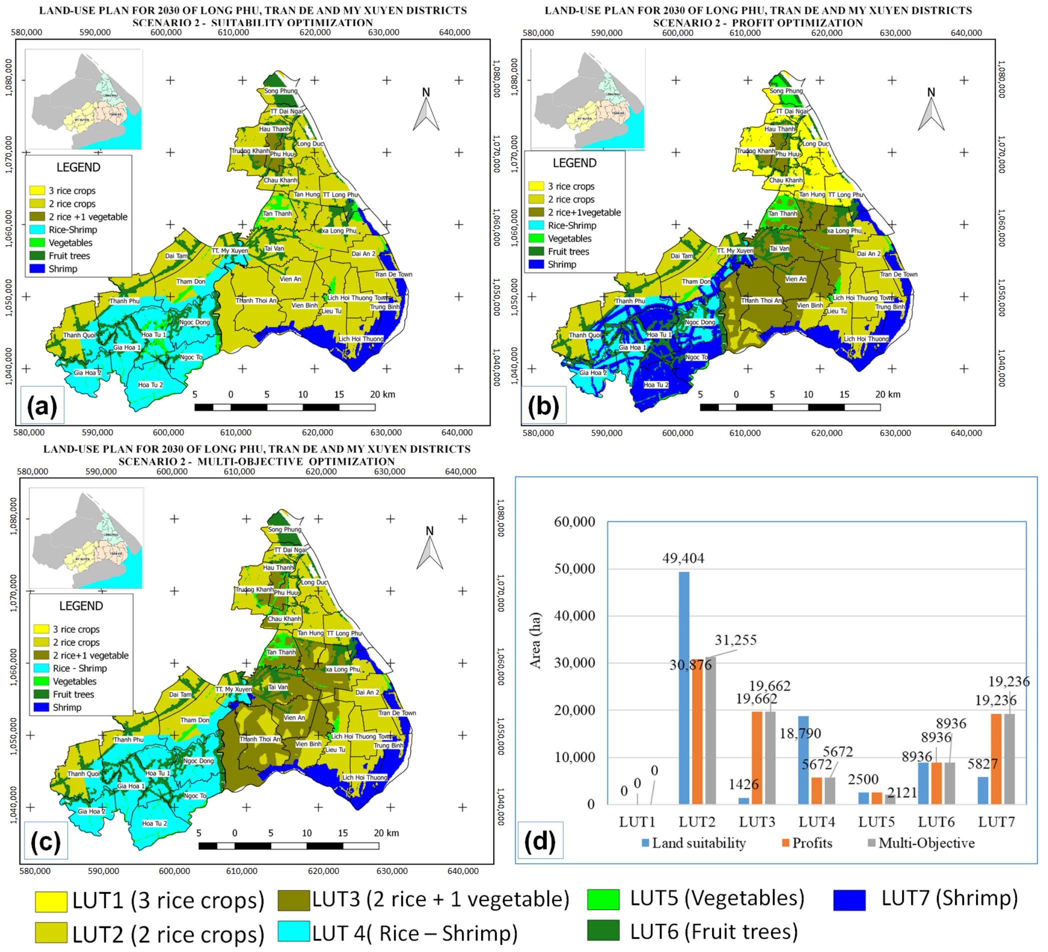


Figure 7. Land-use maps of three alternatives in two scenarios. (**a**) Option 1: maximization of land suitability, (**b**) Option 2: maximization of profits, (**c**) Option 3: maximization multiple objectives, (**d**) land-use area of the three alternative options.

Areas of land-use types of the three alternatives of Scenario 2 are shown in Figure 7d in which three-rice crop land is no longer part of the arrangement in all three options. The two-rice-crop area of Option 1 is significantly higher than that of the other two options because this difference is allocated to rice–vegetable cultivation. Similarly, the rice–shrimp area of Options 2 and 3 of Scenario 2 is much lower than that of Option 1 due to the conversion of rice–shrimp land to shrimp farming land.

3.2.5. Examining for the Best Options

With six possibilities examined for two situations, the total profit of the solutions is a significant component in determining which alternative option to select. However, environmental goals and risk minimization should be taken into account while selecting solutions. Figure 8 depicts the total return of the six alternative options. In both scenarios, the profit maximization plan provides the maximum profit followed by the multi-objective optimal solution, while the adaptive maximization plan yields the lowest profit in the absence of climate change effects.

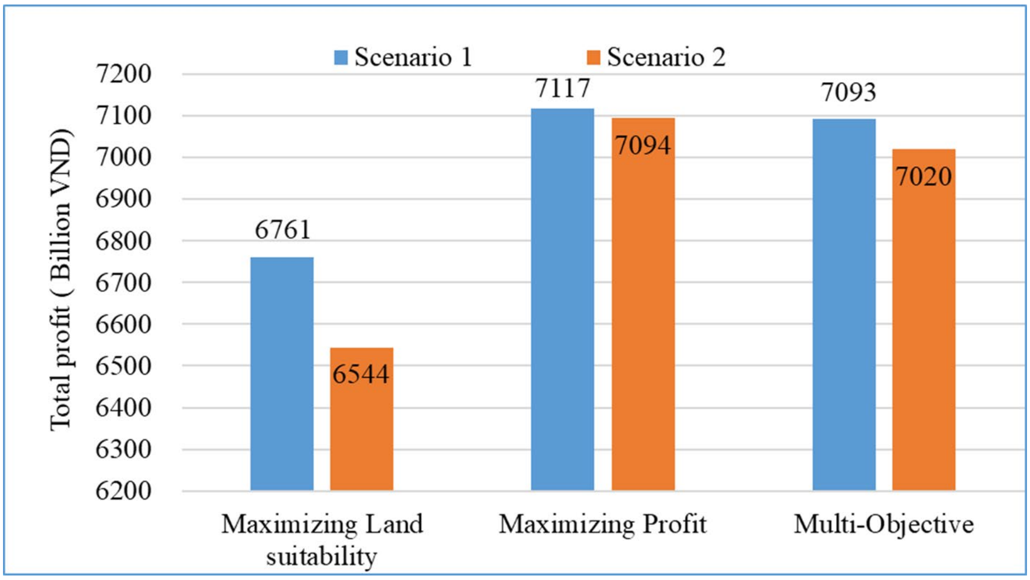
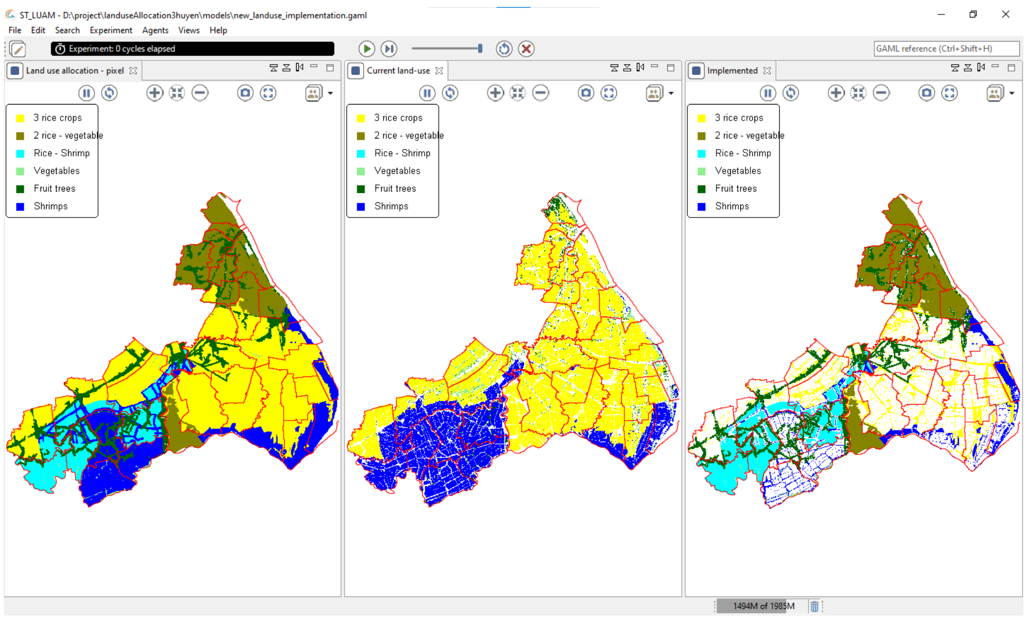


Figure 8. Comparison of the total profit of the two scenarios in 2030.

When the overall profit of the two extremely profitable alternatives is considered, the difference amounts to VND 22.9 billion for Option 2 and VND 72.9 billion for Option 3. However, when considering the environmental component, Option 3 produces the best results in each of the scenarios because it meets the overall goal, which is offered to maximize the synthesis as a foundation for determining the planning possibilities.

The model also includes an overlay feature that allows users to define the areas to be converted for the proposed alternative based on the allotted map. Figure 9 shows the allocation map of the multi-objective alternative of Scenario 1 compared with the 2015 land-use map (Figure 9b) and the conversion map. Figure 9c depicts the darkened regions that should be altered if the strategy is adopted.



(**a**) (**b**) (**c**)

Figure 9. Different maps for 2015 of Scenario 1, with the multi-objective map and the land-use map. (**a**) Optimized map, (**b**) land-use map in 2015, (**c**) areas to be converted.

4. Discussion

4.1. Discussion on the Developed Models

In this study, a predesigned tool was established for optimization and land allocation in the Mekong Delta using proven criteria from prior studies [26,27,29] as well as the environmental and risk assessment criteria of usage patterns. Furthermore, the component of priority policy deployability is incorporated into the land allocation model. The results also demonstrate that integration makes the model easier for planners to utilize due to its predefined impact variables. The optimization findings are then distributed spatially based on socioeconomic characteristics and local infrastructure.

In previous research on the execution of planning options, it was found that capital issues were frequently encountered [37] since they were not integrated into the geographic distribution within the land allocation model. Although the commune's priority for arrangement in terms of space is still limited due to the lack of a criterion for selecting the investment potential value for each pixel, the commune targeted for development in the district's policy will be prioritized for distribution, with more places on the same land unit.

In this study, the utilized value helps to quantify the effect that the levels of elements in the allocated land have, which has been demonstrated in other studies [9] for the risk factors of the land-use types and the environmental benefits of the uses.

To make use of the advantages of each platform, the two modules of the integration model are often deployed for two different platforms as follows: the optimized module is created using the Windows application program interface (Visual Studio); the land allocation module is built on the GAMA platform [36], which is ideal for creating spatial layout models using multi-criteria analysis. The optimization module includes various choices for creating constraint equations that may be freely added and removed, but the program has not been built to incorporate additional elements. In terms of spatial layout, the spatial layout model is used when land units are grouped into one to three land-use types. When numerous land-use types have the same priority, the system demands the creation of a priority list organized through the infrastructure element for the land-use types.

4.2. Discussion on the Proposed Scenarios

In this study, two scenarios, with three alternatives for each scenario, corresponding to normal conditions and under situations of environmental changes were selected for analysis, for which the option of multi-objective optimization is important for reasons of environmental protection and economic development because it has the lowest risk but also the lowest reward. The multi-objective analysis provides land-use options that harmonize the profitability, risk reduction, and negative environmental impact of intensive shrimp farming [9] thank to the utilization of land-use types for rice–shrimp and rice–vegetables [5,6] that are suitable for climate change conditions. The area used for rice–shrimp cultivation has been guaranteed, and the area used for rice crops has been enlarged, allowing people to lower the quantity of rice crops while still ensuring their income.

The optimization was performed based on land units. This resulted in advantages seen in land layout compared with performing optimization across the entire territory when there is conflict in land suitability conditions between land-use types [15,24] and when combining land allocation on each small land unit, and this results in an improvement considering the limitations of land allocation in previous studies, such as those for rice–shrimp and rice land-use types, because these ones are well separated as distinct land units in which each land unit supports a group of land-use types with similar farming characteristics. Therefore, our study demonstrates the advantages in allocating land use to each group with different levels of priority, such as groups including the cultivation of fruit trees, vegetables, rice–vegetables, and different varieties and groups of shrimp and rice–shrimp.

Of the two proposed scenarios, Scenario 2 corresponds to a situation that is highly likely to occur under the impact of climate change and sea level rise. In this scenario, managers have two options to consider as follows: the first is to prioritize economic development in the direction of adapting to saltwater intrusion, thereby increasing people's income (Option 2); or to adapt to multiple goals to reduce risks caused by climate change and the environment toward sustainable development (Option 3). If choosing to prioritize economic development, the area converted to shrimp farming can increase due to the accompanying management policies when there is no constraint for farmers on cultivated area. Managers need to come up with solutions for communes with limited economic and technical conditions in shrimp farming and rice cultivation to minimize the risks due to high technical requirements. In the case of choosing Option 3, managers need to have policies to support the transition to rice–vegetable farming, building a freshwater supply during the dry season to ensure a successful transition, which has also been analyzed in previous studies [7].

4.3. Limitation of the Model

Uncertainties of the proposed options have not been considered, and this is a limitation when proposing long-term planning options. The uncertainty of the options is expressed through two factors: (i) Climate and hydrological factors from the forecast scenario maps of saltwater intrusion uncertain. Land adaptation maps are therefore highly subject to data uncertainty. (ii) Economic investment policy factors can change development goals in the context that Vietnam is shifting its focus to production adapted to nature. However, the options can be updated, which often occurs as there is a review at the half-cycle of the planning process (each 5-year period). This helps to partly limit the uncertainty of the options.

Because users must operate two different modules, this two-module integrated solution remains challenging to use. This limitation can be overcome through extensive research and development of a comprehensive coupling model with the headless mode of the optimized module to make it more technically transparent for users and easier for non-technical managers.

In addition, forecasting of agricultural production is essential for land-use planning, which was implemented in this study. Therefore, it is necessary to expand agricultural production forecasting research to serve as input for the constraints of optimizing land-use area.

4.4. Perspective

Under the conditions of climate change with changing temperatures and rainfall, drought and saltwater intrusion events will persist for longer. Therefore, in future studies, it is necessary to study land-use options where the aspect of maintaining rice cultivation or changing the system of dikes and sluice gates is considered for conversion to shrimp farming. In that case, it is necessary to further survey and analyze the economic and environmental aspects between the options to better understand the risks to shrimp in comparison with reducing rice cultivation from three to two rice crops.

Because Soc Trang is a province with advantages in agricultural development, the model does not consider the influence of urban development on agricultural land use. However, in future research, when studying land distribution, it is necessary to study the conflict between urban expansion factors and agricultural allocation.

5. Conclusions

A land-use optimization model was built including two main components of (1) optimizing the area of agricultural land-use types based on land units and (2) spatial distribution mapping for optimal land-use area. The built optimization model allows for the analysis of optimization according to single-objective functions (such as profit, land suitability) and multi-objective functions (profit, labor, risk reduction, and environmental benefits). The land-use allocation model allows users to solve the problem of land-use allocation for land-use types with opposing farming conditions.

Two scenarios were analyzed for the study area of three districts in Soc Trang province to serve the decision-making process, including (i) a land-use scenario until 2030 under current conditions and (ii) a land-use scenario up to 2030 in conditions of drought and salinity intrusion occurring with high frequency. The results show that, in both scenarios, the multi-objective options give good profit results and, despite not reaching the maximum level, losses are minimized when there are risks of climate change and environmental changes. In particular, Scenario 2 is a situation where there is a period of more frequent drought and saltwater intrusion, so the conversion of cultivation from three to two rice crops or from rice–vegetable cultivation and maintaining the rice–shrimp farming area are necessary for environmentally sustainable development.

From the perspective of land managers and agricultural managers, it is necessary to apply optimization models with many different solutions to find a solution that both ensures food security (rice area according to rice yield requirements) while achieving the highest income for people with a reasonable aquaculture cultivation area. These proposed options are scientifically based and help people to make implementation feasible.

Supplementary Materials: The following supporting information can be downloaded at: https://github.com/nhthao/LandOptimizer.git (accessed on 21 January 2024).

Author Contributions: Q.C.T. conducted modeling and wrote the paper's original draft; T.H.N. (Thao Hong Nguyen) conceptualized the study and wrote the paper's original draft, collected data, built scenarios and the case study, and finalized the paper; V.T.P. reviewed; T.H.N. (Trung Hieu Nguyen) supervised and reviewed. All authors have read and agreed to the published version of the manuscript.

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References

1. GSO. *Mekong Delta—Promoting the Number One Rice Bowl Advantage in the Country 2021*; General Statistics Office (GSO): Hanoi, Vietnam, 2021.
2. Espagne, E.; Ngo-Duc, T.; Nguyen, M.-H.; Pannier, E.; Woillez, M.-N.; Drogoul, A.; Huynh, T.P.L.; Le, T.T.; Nguyen, T.T.H.; Nguyen, T.T.; et al. *Climate Change in Viet Nam, Impacts and Adaptation: A COP26 Assessment Report of the GEMMES Viet Nam Project*; Agence Française de Développement: Paris, France, 2021.
3. Anh, D.L.T.; Anh, N.T.; Chandio, A.A. Climate Change and Its Impacts on Vietnam Agriculture: A Macroeconomic Perspective. *Ecol. Inform.* **2023**, *74*, 101960. [CrossRef]
4. Wassmann, R.; Hien, N.X.; Hoanh, C.T.; Tuong, T.P. Sea Level Rise Affecting the Vietnamese Mekong Delta: Water Elevation in the Flood Season and Implications for Rice Production. *Clim. Change* **2004**, *66*, 89–107. [CrossRef]
5. Loc, H.H.; Thi Hong Diep, N.; Can, N.T.; Irvine, K.N.; Shimizu, Y. Integrated Evaluation of Ecosystem Services in Prawn-Rice Rotational Crops, Vietnam. *Ecosyst. Serv.* **2017**, *26*, 377–387. [CrossRef]
6. Bong, B.B.; Bo, N.V.; Son, N.H.; Tung, L.T.; Tu, T.Q.; Toan, T.Q.; Yen, B.T.; Trung, N.D.; Labios, R.V.; Sebastian, L.S. *Adaptation Options for Rice-Based Cropping Systems in Climate Risk-Prone Provinces in the Mekong River Delta: An Assessment Report*; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS): Wageningen, The Netherlands, 2018.
7. Truong, Q.C.; Drogoul, A.; Gaudou, B.; Taillandier, P.; Huynh, N.Q.; Nguyen, T.H.; Minderhoud, P.; Nguyen Thi Thu, H.; Espagne, E. An Agent-Based Model for Land-Use Change Adaptation Strategies in the Context of Climate Change and Land Subsidence in the Mekong Delta. *Sustainability* **2023**, *15*, 5355. [CrossRef]
8. Truong, Q.C.; Gaudou, B.; Van Danh, M.; Quang Huynh, N.; Drogoul, A.; Taillandier, P. A Land-Use Change Model to Study Climate Change Adaptation Strategies in the Mekong Delta. In Proceedings of the 2021 RIVF International Conference on Computing and Communication Technologies (RIVF), Hanoi, Vietnam, 19–21 August 2021; pp. 1–6.
9. Trang, N.T.; Tu, V.H.; Kopp, S.W. Trade-Offs between Economic and Environmental Efficiencies in Shrimp Farming: Implications for Sustainable Agricultural Restructuring in the Vietnamese Mekong Delta. *Environ. Dev. Sustain.* **2023**, *25*, 2670–2687. [CrossRef]
10. FAO. *Guidelines for Land-Use Planning*; FAO Development Series; FAO: Rome, Italy, 1993; ISBN 92-5-103282-3.

11. FAO. *A Framework for Land Evaluation*; Soil Resources, Management and Conservation Service, Ed.; FAO soils bulletin; 2. print.; FAO: Rome, Italy, 1981; ISBN 92-5-100111-1.
12. Yamamura, K.; Tamura, N. Finding All Solutions of Separable Systems of Piecewise-Linear Equations Using Integer Programming. *J. Comput. Appl. Math.* **2012**, *236*, 2844–2852. [CrossRef]
13. Delphin, S.; Snyder, K.A.; Tanner, S.; Musálem, K.; Marsh, S.E.; Soto, J.R. Obstacles to the Development of Integrated Land-Use Planning in Developing Countries: The Case of Paraguay. *Land* **2022**, *11*, 1339. [CrossRef]
14. Chuvieco, E. Integration of Linear Programming and GIS for Land-Use Modelling. *Int. J. Geogr. Inf. Syst.* **1993**, *7*, 71–83. [CrossRef]
15. Mellaku, M.; Reynolds, T.; Woldeamanuel, T. Linear Programming-Based Cropland Allocation to Enhance Performance of Smallholder Crop Production: A Pilot Study in Abaro Kebele, Ethiopia. *Resources* **2018**, *7*, 76. [CrossRef]
16. Aerts, J.C.J.H.; Eisinger, E.; Heuvelink, G.B.M.; Stewart, T.J. Using Linear Integer Programming for Multi-Site Land-Use Allocation. *Geogr. Anal.* **2003**, *35*, 148–169. [CrossRef]
17. Phinyoyang, A.; Ongsomwang, S. Optimizing Land Use and Land Cover Allocation for Flood Mitigation Using Land Use Change and Hydrological Models with Goal Programming, Chaiyaphum, Thailand. *Land* **2021**, *10*, 1317. [CrossRef]
18. Liao, G.; He, P.; Gao, X.; Lin, Z.; Huang, C.; Zhou, W.; Deng, O.; Xu, C.; Deng, L. Land Use Optimization of Rural Production–Living–Ecological Space at Different Scales Based on the BP–ANN and CLUE–S Models. *Ecol. Indic.* **2022**, *137*, 108710. [CrossRef]
19. Vũ, P.T.; Khương, N.T.A.; Trí, L.Q.; Huy, V.T. Application of mathematical optimization method in agricultural land use—Case study in Vi Thuy district, Hau Giang province. *Can Tho Univ. J. Sci.* **2016**, *44*, 38–47. [CrossRef]
20. Vũ, P.T.; Lộc, T.T.; Trí, L.Q.; Huy, V.T.; Trung, N.H. Enhancing land use efficiency for income optimization of farm households in Tra Hat hamlet of Chau Thoi commune, Vinh Loi district, Bac Lieu province. *Can Tho Univ. J. Sci.* **2017**, *51*, 54–63. [CrossRef]
21. Verburg, P.H.; Overmars, K.P. Dynamic Simulation of Land-Use Change Trajectories with the Clue-S Model. In *Modelling Land-Use Change: Progress and Applications*; Koomen, E., Stillwell, J., Bakema, A., Scholten, H.J., Eds.; The GeoJournal Library; Springer: Dordrecht, The Netherlands, 2007; pp. 321–337. ISBN 978-1-4020-5648-2.
22. Valbuena, D.; Verburg, P.H.; Bregt, A.K.; Ligtenberg, A. An Agent-Based Approach to Model Land-Use Change at a Regional Scale. *Landsc. Ecol.* **2010**, *25*, 185–199. [CrossRef]
23. Wu, C.; Chen, B.; Huang, X.; Dennis Wei, Y.H. Effect of Land-Use Change and Optimization on the Ecosystem Service Values of Jiangsu Province, China. *Ecol. Indic.* **2020**, *117*, 106507. [CrossRef]
24. Quang, T.C.; Diem, P.K.; Minh, V.Q.; Vu, P.T.; Vu, P.H.; Chinh, P.T. An Analysis of Land Use Options Using CLUMondo Model to Promote Agricultural Restructuring in the Mekong Delta's Coastal Area in Vietnam. *Agric. Sci. Dig.—Res. J.* **2023**, *43*, 482–489. [CrossRef]
25. Lambin, E.; Geist, H.J. Causes of Land-Use and Land-Cover Change. Available online: http://www.eoearth.org/view/article/150964/ (accessed on 23 March 2015).
26. Santiphop, T.; Shrestha, R.P.; Hazarika, M.K. An Analysis of Factors Affecting Agricultural Land Use Patterns and Livelihood Strategies of Farm Households in Kanchanaburi Province, Thailand. *J. Land Use Sci.* **2012**, *7*, 331–348. [CrossRef]
27. Liu, J.; Xia, M. Influencing Factors Analysis and Optimization of Land Use Allocation: Combining MAS with MOPSO Procedure. *Sustainability* **2023**, *15*, 1401. [CrossRef]
28. Loi, L.T.; Tien, L.T.M.; Vu, P.T. Analysis of the factors affecting efficiency of agricultural land use patterns in the Ba Tri district, Ben Tre province. *Can Tho Univ. J. Sci.* **2016**, *43*, 80–92. [CrossRef]
29. Vu, P.T.; Tri, L.Q.; Dat, N.T.; Huy, V.T.; Nuong, L.T.; Trung, N.H. Using multi-criteria decision analysis in agricultural land uses in Bac Lieu province. *Can Tho Univ. J. Sci.* **2014**, *31*, 106–115.
30. Sofi, N.A.; Ahmed, A.; Ahmad, M.; Bhat, B.A. Decision Making in Agriculture: A Linear Programming Approach. *Int. J. Mod. Math. Sci.* **2015**, *13*, 160–169.
31. Tuan Anh, B.; Bong Dinh, N.; Tam Thi, D. Some Factors Which Influence management of Agricultural Land Use in Sontay Town, Hanoi City. *J. Sci. Devel.* **2013**, *11*, 654–662.
32. Tri, L.Q.; Chi, V.V.; Vu, P.T.; Kiet, N.H.; Binh, N.T.S.; Guong, V.T. Evaluating the changes of soil properties and land use at three coastal districts in Soc Trang province. *Can Tho Univ. J. Sci.* **2008**, *9*, 59–68.
33. Nghi, N.Q.; Hien, L.T.D. Market risk in agriculture of households in the Mekong Delta. *Can Tho Univ. J. Sci.* **2014**, *33*, 38–44.
34. Yamane, T. *Statistics: An Introductory Analysis*, 2nd ed.; Harper and Row: New York, NY, USA, 1967.
35. lp_solve Introduction to Lp_solve 5.5.2.5. Available online: http://web.mit.edu/lpsolve/doc/ (accessed on 4 June 2019).
36. Taillandier, P.; Gaudou, B.; Grignard, A.; Huynh, Q.-N.; Marilleau, N.; Caillou, P.; Philippon, D.; Drogoul, A. Building, Composing and Experimenting Complex Spatial Models with the GAMA Platform. *GeoInformatica* **2019**, *23*, 299–322. [CrossRef]
37. Enoguanbhor, E.C.; Gollnow, F.; Walker, B.B.; Nielsen, J.O.; Lakes, T. Key Challenges for Land Use Planning and Its Environmental Assessments in the Abuja City-Region, Nigeria. *Land* **2021**, *10*, 443. [CrossRef]

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