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Agricultural crop zoning with mixed integer programming for aromatic coconut in Ratchaburi Province

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Abstract

Nowadays, the main concern in agricultural production is to balance the demand and supply to avoid the supply-over-demand problem. Agricultural zoning is a preferred solution to the problem, allowing farmers and policymakers to choose the most suitable economic crop for a particular area. The land suitability, factory locations and distances, profits, and crop growth costs must be considered when choosing optimal areas. For optimization problems, Mixed Integer Programming (MIP) is one of the most common mathematical optimization tools. In this study, we employed a solver called the Gurobi optimizer to find the target areas for the given crop. In this multi-criteria optimization problem, the goal is to maximize the land suitability of the desired crop, maximize profit, minimize the switching between the current and the new crop, and minimize the distance from the areas to the nearest market. The total amount of crop production should not exceed the capacity of the factories and the market demand. We apply the models to the real-world problem by assuming that the desired crop is Sweet Young Coconut (Aromatic Coconut) in Ratchaburi province. Land suitability of crops, economic inputs, and market locations for this study are obtained from the Agri-Map: Agricultural Map for Adaptive Management. We test the efficiency of the models with two scenarios: with and without factory purchasing capacity limitation. The results show that the model with factory purchasing capacity constraints is applicable for choosing the most suitable target areas to balance the crop supply with the market demand.

Keywords: Agricultural zoning, Agri-map, Gurobi, Mixed integer programming

1. Introduction

Agricultural zoning is a regulatory approach that has been used to preserve agricultural areas of a country. Promoting appropriate land use, balancing the crop supply with the market demand, and developing a systematic control of the agricultural program at a provincial level are the main objectives of agricultural zoning.

Since 2013, the Thai government has announced the agricultural economics crop zoning comprising thirteen crops, five livestock, and two fisheries. The major crops are coconut, cassava, rice, sugarcane, hevea, oil palm, maize, pineapple, rambutan, longan, durian, mangosteen, and coffee. Also, the five livestock are chicken, beef cattle, dairy cattle, swine, and hen. Moreover, the two fisheries are freshwater animals and sea prawns. The Ministry of Agriculture and Cooperatives (MOAC) has scheduled a road map to speed up the zoning development in 2013–2032, a total of 20 years [1]. In 2016, the MOAC and the National Electronics and Computer Technology Center (NECTEC) created the Agri-Map application [2] to more efficiently manage the supply and demand of farm products as it moves to comprehensively reform the agricultural sector, which provides suitability information for land in each area and specific crop production based on soil, temperature, water, rainfall level, and factory locations. Agri-Map will enable government agencies to assess the specific amount of farm products to produce in different areas at various times of the year to prevent oversupply. The Agri-Map is expected to help raise the productivity in each area by offering better suitability crops for the farmer area. Moreover, the Ministry of Agriculture and Cooperatives; MOAC already set the Agri-Map as a crucial tool for promoting and adjusting production in the agricultural development plan under the 12th and 13th national economic and social development plan (2017-2021, 2022-2026) [3-5].

Therefore, policy officials like the Land Development Department (LDD) use this tool to formulate strategies for introducing additional suitable land for plantations. That is not only for aromatic coconuts but also for other crops that can create values according to the agricultural area of the province. The strategies have been employed as guidelines to promote agricultural zoning [6]. The cropland allocation optimization model was developed on the potential area that has made the niche products, such as the sweet young coconut in Ratchaburi, a Geographical Indications (GI) crop [7]. The agricultural zoning for aromatic coconuts is mandated by Agricultural Land Use Allocation under Current and Projected Scenarios by Ratchaburi Province Agriculture and Cooperatives Office [8].

One of the most common optimization tools is Mixed Integer Programming or MIP, an extension of linear used to solve the optimization problem. The MIP has been applied to solve various optimization problems in agriculture, such as mixed crop selection by choosing the best combination of crops to cultivate cropland [9]. The MIP is also implemented in a mixed fruit-vegetable cropping system that shows a promising way of ensuring environmentally sustainable agricultural production in response to the challenge of fulfilling local market requirements [10]. For the selecting and allocating Land Parcels Problem (SA-LPP), the MIP has been proposed to optimize the selection and allocation of land parcels with rectangular shapes in small areas available for food production [11]. Furthermore, MIP has been applied to support decision-making for production planning of the supply chain of tangerines [12] and coffee [13].

Here, we use a MIP-based Gurobi solver [14] to optimize land use that matches its suitability, balance the crop supply with the market demand, and develop a systematic control of the agricultural program. We apply the model to the real-world problem by assuming that the desired crop is Sweet Young Coconut in Ratchaburi province.

2. Method

2.1 Problem description and data preparation

The problem is where to change the area of any crop A to the desired crop B, meanwhile maximizing crop B's suitability, minimizing crop A's suitability, maximizing net profit, and minimizing the distance from the selected areas to the nearest purchasing source. The sweet rice coconut at Ratchaburi cultivated area data and net profit per 0.16 ha of each crop were provided by Agri-Map, and market or factory locations were provided by the Department of Industrial Wors [15]. The total coconut increasing demand was approximated by Thailand demand data and original production capacity from the Department of agriculture [7]. The remaining purchasing capacity of each factory is approximated by assuming the current crop serves the nearest factory, and the factory still has 50 percent of its current production capacity.

To provide the candidate area, we divided interested land into 1-kilometer squares (100 ha), with each square designated its ID to identify it. These squares will be applied to find each square's suitability and current use between one crop and another. Each square will be assessed to find what parts are currently being used while showing the suitable parts. Non-planted crop B areas with high, modest, and low suitability are chosen as candidates. The distance between the center of any square i and any source j is calculated by the Haversine formula [16].

The suitability classifies into five classes based on FAO Land suitability classifications [17] high (S1), modest (S2), low (S3), Not suit (N), and not specified (N/A). To calculate the suitability score, we mark each pair of the current and desired crop suitability with various scores, as shown in Table 1. We weighted that score with its area and normalized its values to the range from zero to one across the candidate variables by Min-Max normalization [18]. Min-Max normalization, also known as Min-Max scaling, is a technique used to scale a variable's values to a specific range, such as from zero to one. We also use Min-Max normalization to normalize distance and profit.

Table 1 Suitability to Suit Score conversion.

Current crop \ Coconut	S1	S2	S3	N
S1	3	2	1	0
S2	4	3	2	1
S3	5	4	3	2
N	6	5	4	3

2.2 Mathematical model

To formulate the mathematical model, we let n be the number of candidates field, k be the number of purchasing sources, D_{ij} be the distance between the center of field i and source j calculated by Haversine formula for $i \in I$ and $j \in J$ where $I = 1, 2, ..., n$, and $J = 1, 2, ..., k$. The decision variable K_{ij}, Y_i, X_{ij}, and parameters notation are defined as

Notation

Decision variable

X_{ij} = proportion of the amount that field i serve factory j,

$Y_i = \begin{cases} 1, & if\ field\ i\ is\ selected \\ 0, & otherwise \end{cases}$ *****

$K_{ij} = \begin{cases} 1, & if\ field\ i\ is \text{ serve factory } j \\ 0, & otherwise \end{cases}$

Parameters

D_{ij} = Normalize distance from field i to source j

S_i = Normalize Suitability score of field i

P_i = Normalize profit of field i

A_i = Area of field i (ha)

N_i = Amount of product from field i (kg)

C_j = purchasing capacity of factory j

X = total market demand

It is a common practice to formulate the optimization problem by including multiple conflicting objectives in the objective function. This is because MIP models are often used to find a solution that optimizes multiple conflicting objectives simultaneously. By including all the objectives in a single objective function, the optimization algorithm can find the best solution that balances the trade-offs between the different objectives. The optimized solution should be considered best when it has the balance of all objectives and is not only optimized for one objective.

The objective is to maximize $\sum_{i=1}^{n} S_i Y_i + \sum_{i=1}^{n} P_i Y_i - \sum_{i=1}^{n} \sum_{j=1}^{k} D_{ij} K_{ij}$

s.t.

$$\sum_{i=1}^{n} N_i Y_i \leq X, \qquad (1)$$

$$\sum_{j=1}^{k} X_{ij} = Y_i, \quad \forall i \in I, \qquad (2)$$

$$\sum_{i=1}^{n} N_i X_{ij} \leq C_j, \quad \forall j \in J, \qquad (3)$$

$$X_{ij} \leq K_{ij}, \quad \forall i \in I, \forall j \in J \qquad (4)$$

$$0 \leq X_{ij} \leq 1 \qquad (5)$$

$$Y_i, K_{ij} \in \{0,1\} \quad \forall i \in I, \forall j \in J \qquad (6)$$

Constraint 1 ensures that the total product amount from the selected area is less than or equal to the total market demand to avoid the oversupply problem. Constraint 2 states that purchasing sources purchase all products from selected fields, and constraint 3 specifies that purchasing source can obtain a product that does not exceed its purchasing capacity. Constraint 4 ensures that the amount of field i serve factory j is more than 0 if and only if field i decides to serve factory j. Constraint 5 and constraint 6 are variable constraints.

3. Numerical experiments and application

3.1 Real case data

We applied our model to a real case of sweet young coconut in Ratchaburi province, Western Thailand. The data on the sweet young coconut at Ratchaburi cultivated area was provided by the Agri-Map, the purchasing source was provided by the Department of industrial work, and the total coconut demanding amount was from the Department of agriculture. The total coconut increasing demand was approximated by Thailand's demand data and original production capacity from the Department of agriculture.

For this section, we divided problems into two cases. First, we assume that each factory has no capacity limitation by letting the right-hand side of the capacity constraint be infinite. In another case, we approximated the remaining purchasing capacity of each factory by assuming that each crop's fields serve the nearest factory and that the factory still has 50 percent of its current production capacity. The approximated remaining purchasing capacities are shown in Table 2.

Table 2 The remaining purchasing capacity of the factories.

Factory id	Total factory's capacity (kg)	Factory id	Total factory's capacity (kg)	Factory id	Total factory's capacity (kg)
1	202,422.78	10	19,239,251.42	19	16,550,189.05
2	505,903.47	11	31,235,925.90	20	14,854,056.37
3	478,705.92	12	22,742,242.47	21	13,479,473.38
4	3,857,470.02	13	31,929,271.34	22	30,398,984.49
5	4,289,293.61	14	1,368,404.00	23	15,740,194.82
6	14,357,940.90	15	5,852,836.05	24	44,606,401.65
7	12,826,164.26	16	14,019,311.23	25	9,740,802.52
8	4,926,722.07	17	2,816,837.89	26	4,304,737.09
9	3,359,004.14	18	86,963,511.82	27	7,945,910.25

Figure 1 (A) displays 12 crops' land-use and (B) coconut's land-suit in Ratchaburi province. The areas where the suitability of coconut: S1, S2, or S3 and N intersect with the landuse of other crops are chosen to be candidates, as shown in Figure 2 with the coconut purchasing source locations.

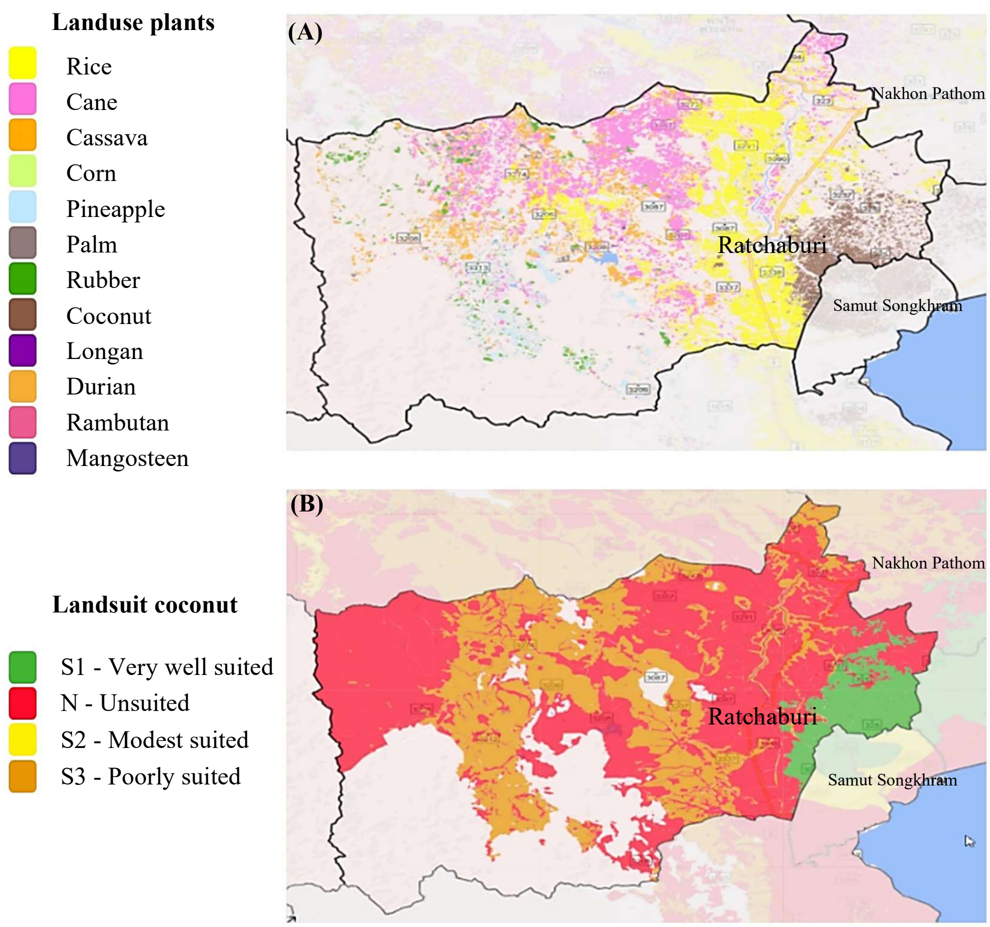

Figure 1 (A) Crops' landuse; (B) Coconut's landsuit in Ratchaburi province from Agri-Map [2]

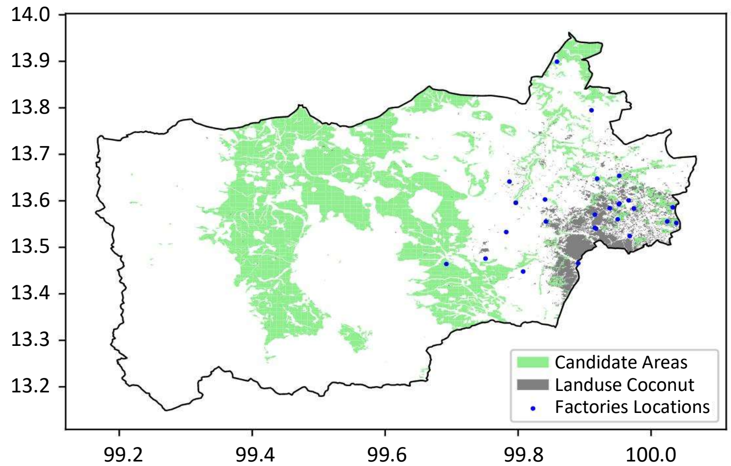

Figure 2 Candidate areas, current landuse coconut, and factories locations

Landuse areas on the suitability level of each crop that can be grown on suitability layers S1, S2, and S3 of coconut are shown in Table 3. Candidate areas classified by coconut suitability layers S1, S2, and S3 are 651.33 ha, 25.18 ha, and 60,998.38 ha, respectively.

Table 3 Landuse areas on the suitability level of each crop that can be planted on suitability layers S1, S2, and S3 of coconut (in ha).

Crop name	S1	S2	S3	N	Total
cassava	58.71	12,786.69	0.80	0.00	12,846.20
rice	1,400.16	1.16	8,496.46	224.51	10,122.28
corn	31.33	62.47	0.62	0.00	94.42
cane	3,080.29	3,662.75	21,410.27	5.10	28,158.41
rubber	0.68	113.16	1,708.01	2,027.67	3,849.52
longan	115.53	51.50	55.04	0.09	222.16
palm	0.00	0.00	0.00	1,516.19	1,516.19
pineapple	121.21	4,690.91	45.39	0.01	4,857.52
durian	0.00	0.00	0.00	5.29	5.29
rambutan	0.00	0.00	0.00	2.91	2.91
Total	4,807.91	21,368.63	31,716.58	3,781.76	61,674.88

Table 4 The remaining purchasing capacity of the factories and the output from the models delivered to each factory in kilograms.

Factory id	Total factory's capacity (kg)	Without capacity (kg)	With capacity (kg)	Factory id	Total factory's capacity (kg)	Without capacity (kg)	With capacity (kg)
1	202,422.78	18,814.99	198,855.20	15	5,852,836.05	19,996,480.00	5,795,162.00
2	505,903.47	4,163,242.00	463,091.30	16	14,019,311.23	7,022,164.00	13,943,730.00
3	478,705.92	2,013,790.00	463,099.80	17	2,816,837.89	118,000,000.0	2,759,351.00
4	3,857,470.02	316,390.90	3,839,479.0	18	86,963,511.82	6,198,824.00	86,840,037.00
5	4,289,293.61	7,888,108.00	4,289,294.0	19	16,550,189.05	338,482.50	9,393,771.00
6	14,357,940.90	233,749.20	233,749.20	20	14,854,056.37	2,091,590.00	3,103,040.00
7	12,826,164.26	537,916.20	537,916.20	21	13,479,473.38	901,935.10	901,935.10
8	4,926,722.07	281,179.70	4,637,550.0	22	30,398,984.49	3,479,503.00	30,344,334.00
9	3,359,004.14	6,433.53	6,433.53	23	15,740,194.82	4,818,117.00	15,623,133.00
10	19,239,251.42	1,712,974.00	10,130,471	24	44,606,401.65	284,945.30	1,179,667.00
11	31,235,925.90	193,700.90	14,458,152	25	9,740,802.52	64,697,749.00	9,724,714.00
12	22,742,242.47	20,237.31	22,502,075	26	4,304,737.09	326,076.20	326,076.20
13	31,929,271.34	532,790.80	31,921,112	27	7,945,910.25	19,850,378.00	7,893,774.00
14	1,368,404.00	16,456,273.0	1,368,404.0				

3.2 Results

We implemented and solved the model using Gurobi Optimizer version 9.5.1 build v9.5.1rc2 with a default setting by python. The cropland allocation model is set according to the optimization model showing where cropland cultivating coconut should be allocated to maximize suitability and minimize the distance to factories subjected to factories' purchasing capacity constraints. Gurobi uses several algorithms, including primal and dual simplex and branch and bound, to solve mixed-integer linear programming problems and is guaranteed to find the optimal solution if enough time is given.

In this paper, we set a time limit of 1 hour to find the optimal solution for both cases. The amount of product serving each factory is shown in Table 4.

Table 4 shows that without a capacity case, the amount of crop product serving factories 5, 14, 15, 17, and 27 exceeds the factories' capacity. Then after taking capacity into a model, it tries to balance crop products by distributing crop products to factories that still have remaining purchasing capacity, as shown in Figure 3. The color area represents areas selected to serve the factory, which is the same color, and the grey areas represent the current landuse coconut. The average distance from the selected fields to the service factory is 20.53 and 14.51 km for with and without capacity limitation cases, respectively. The selected areas of other crops on suitability layers S1, S2, and S3 of coconut are classified by suitability (in ha) for a case without capacity and a case with capacity, as shown in Tables 5 and 6. Selected areas classified by coconut suitability are shown in Table 7.

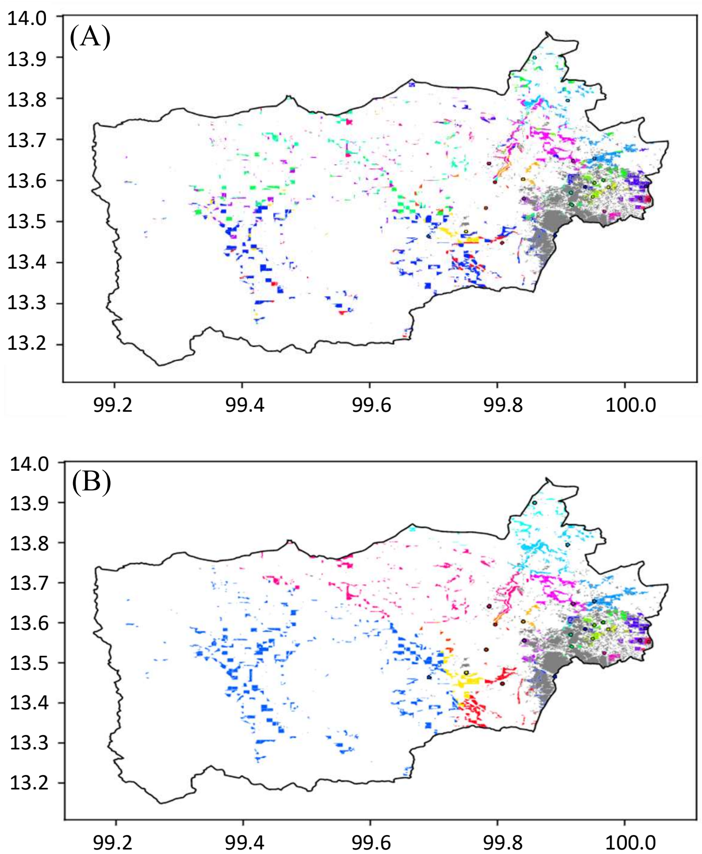

Figure 3 Cropland allocation maps according to the optimization model. (A) without capacity; (B) with capacity

Table 5 Selected areas from without capacity case of other crops on suitability layers S1, S2, and S3 of coconut classified by suitability (in ha).

Crop name	S1	S2	S3	N
cassava	7.61	987.81	0.59	0.00
rice	704.13	0.03	688.17	86.48
corn	23.28	10.95	0.00	0.00
cane	577.23	257.09	1,211.29	5.10
rubber	0.26	1.19	85.05	130.99
longan	105.18	19.33	0.00	0.09
palm	0.00	0.00	0.00	101.16
pineapple	31.97	390.93	15.02	0.00
durian	0.00	0.00	0.00	0.00
rambutan	0.00	0.00	0.00	2.91
Total	1,449.65	1,667.33	2,000.11	326.73

Table 6 Selected areas from the capacity case of other crops on suitability layers S1, S2, and S3 of coconut classified by suitability (in ha).

Crop name	S1	S2	S3	N
cassava	7.61	995.69	0.59	0.00
rice	701.33	0.03	702.43	86.48
corn	23.28	9.82	0.00	0.00
cane	568.08	262.68	1,192.38	5.10
rubber	0.26	1.19	85.05	130.99
longan	105.18	19.33	0.00	0.09
palm	0.00	0.00	0.00	104.89
pineapple	31.97	391.53	15.02	0.00
durian	0.00	0.00	0.00	0.00
rambutan	0.00	0.00	0.00	2.91
Total	1,437.70	1,680.27	1,995.46	330.46

Table 7 Selected areas classified by coconut suitability.

	Candidate (ha)	With capacity (ha)	Without capacity (ha)
S1	651.33	478.19	478.19
S2	25.18	25.18	25.18
S3	60,998.38	4,940.53	4,940.46
Total	61,674.88	5,443.90	5,443.82

Based on the results, both cases almost selected the same fields. However, with purchasing a capacity case, the model tries to distribute crop products to factories that still have remaining purchasing capacity, so purchasing capacity case is applicable for choosing the most optimal target areas to balance the supply of crops with the market demand.

4. Conclusion and future work

Agricultural zoning is a regulatory approach that has been used to preserve agricultural areas of a country. This study uses mixed integer programming solver by Gurobi optimizer to optimize cropland by balancing the supply of crops with the market demand. This study also develops a systematic control of the agricultural program at a provincial level. We apply the model to the real-world problem by assuming that the desired crop is Sweet Young (Aromatic) Coconut, a GI crop in Ratchaburi province.

We experiment with two cases, with and without factory purchasing capacity limitation. The results obtained by running models with factory purchasing capacity constraints improve the efficiency of choosing suitable areas according to purchasing capacities and locations. Therefore, the model with factory purchasing capacity is more practical for deciding the target area to balance the supply of crops with the market demand than the model without capacity constraints.

Due to the lack of data and time, many adaptations, tests, and experiments have been left for the future. The experiments with actual data are usually very time-consuming. They require hours or days to prepare data to finish a single run. Moreover, there is still a lack of purchasing capacity data, etc. Future work may need to consider different methods to solve the model or add additional real-world objectives/constraints, such as trying to choose neighbor fields or assuming that some fields have been assigned to a fixed factory.

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