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Exploring Optimal Paddy-Upland Rotation Systems Using a Multi-Objective Genetic Algorithm: Economic, Environmental, and Food Security Performance

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Abstract

This paper examines optimal paddy-upland rotation systems, considering the trade-offs between economic, environmental, and food security indicators (crop revenues, nitrogen fertilizer inputs, and food calories, respectively). A regional optimization model targeted at a rich rice-producing region in Hokkaido, Japan was built for the analysis. It incorporates economic and food security objective functions to be maximized and an environmental objective function to be minimized under land-use constraints. A multi-objective genetic algorithm was applied to solve the multi-objective optimization problem at the regional level. Using k-means clustering, Pareto-optimal solutions were classified into three types of clusters: economic and food security, balanced, and environmental. The total crop revenue, total nitrogen fertilizer input, and total food calories were 11.5%, 4.8%, and 42.0% higher, respectively, for the economic and food security cluster than those for the environmental cluster. Considering the low nitrogen contamination in groundwater in the targeted region, the four-year paddy-upland rotation systems based on dry direct-seeded rice, spring wheat, soybeans, and direct-seeded sugar beets, which represent the highest adoption rate (83.9%) in the economic and food security cluster, should be promoted regionally to prioritize maximization of crop revenues and food calories. These findings are useful for local policymakers.

Discipline: Social Science
Additional key words: crop revenue, food calories, land use, multi-objective optimization, nitrogen fertilizer inputs

Introduction

An essential foundation for the productivity and sustainability of a cropping system is a long, diverse crop rotation system (Cook 2006). Japanese rice farmers have generally accepted the rotation of rice and upland crops required by rice production adjustments designed to reduce over-production (Nishida 2016). In Hokkaido, an island north of Japan with excess rice production capacity, continuous cropping and rotating wheat and soybeans in drained paddy fields has been widely practiced because of favorable subsidies and the ease of adopting these crops (HCAES 2004). However, such production has caused severe soil degradation and yield declines (HCAES 2004).

To alleviate these problems, Hokkaido requires an extension of the paddy-upland rotation system (HCAES 2004, SAEC 2019). Paddy-upland rotation offers several advantages, including destroying aerobic pathogens in flooded paddy fields, suppressing weeds, improving the physical properties of soil, and using soil nutrients effectively (HCAES 2004). Therefore, paddy-upland rotation for three (rice, soybeans, and wheat) and four years (rice and three other upland crops) has been recommended (Saito 2013). Four-year paddy-upland rotation is better than three-year paddy-upland rotation because of its diverse crop rotation and increased profitability (Saito 2013).

Optimization modeling at the regional level for crop production plans is useful for local stakeholders exploring alternative crop rotation systems. Regional optimization models have been built to clarify the trade-offs between economic and environmental performance in cropping decisions (Heidari et al. 2021). However, as Japan has a low food self-sufficiency ratio (MAFF 2022), food security indicators must be included in regional

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optimization models in addition to the economic and environmental indicators.

The concept of crop rotation has been incorporated into many cropping plan decision models (Dury et al. 2012). For example, based on the trade-offs between economic, environmental, and food security performance, studies have examined paddy-upland rotation systems in a wetland region of France (Delmotte et al. 2017), upland crop rotation systems in the North China Plain (Groot & Yang 2022), and upland crop rotation systems in an inland river basin of China (Hou et al. 2023). However, few studies have used regional optimization modeling to consider the trade-offs between these indicators in identifying optimal paddy-upland rotation systems in Asia.

This paper examines Japan's optimal paddy-upland rotation systems, considering the trade-offs between economic, environmental, and food security indicators. The analysis formulated a regional optimization model focusing on a rich rice-producing region in Hokkaido as a multi-objective optimization problem.

Materials and methods

1. Description of the study area

The Sorachi region is located in the west-central part of Hokkaido (Fig. 1). In 2020, its total cultivated area was 113,600 hectares (ha), which included 91,100 ha of paddy fields (41.0% of those in Hokkaido and 3.8% of those in Japan) (HDAO 2021). Of these, 44,700 ha were devoted to rice cultivated as food (HDAO 2021). The typical soil types included lowland soils, peat soils, upland soils, and volcanic soils, which made up 53.7%, 23.6%, 14.9%, and 7.9%, respectively, of the total area of the paddy fields (Hashimoto 2008).

Severe soil degradation and yield decreases have been caused in drained paddy fields of the Sorachi region by continuously cropping winter wheat, repeatedly growing soybeans, and rotating soybeans following winter wheat (SAEC 2019, Saito 2013). Thus, paddy-upland rotations, especially four-year systems, are strongly encouraged in this region.

2. Indicators of the candidate crops for four-year paddy-upland rotation systems

This study incorporated the four-year paddy-upland rotation systems of rice (cultivated in year 1 of the rotation) and three different upland crops (grown in years 2-4 of the rotation) into a regional optimization model. As shown in Table 1, dry direct-seeded rice (DR), conventional winter wheat (WW), winter wheat under soybean-wheat relay intercropping (WWR), conventional spring wheat (SW), spring wheat seeded in early winter (SWE), soybeans (SY), rapeseed (RS), and direct-seeded sugar beets (DSB) were selected as candidates for the four-year paddy-upland rotation systems (SAEC 2019). WWR indicates the cultivation of winter wheat seeded before harvesting SY (DAHG 2024). Of the candidate crops recommended by the Sorachi Agricultural Extension Center (SAEC 2019), transplanted rice, maize, and onion were excluded for the following reasons: (1) conversion of paddy fields to upland fields is easier for DR than for transplanted rice (Takemoto 2021); (2) the demand for maize for animal consumption is low in the Sorachi region because the number of livestock is small (SAEC 2019); and (3) onions are assumed to be cultivated

Fig. 1. Location of the study area in Hokkaido
This map was made by processing the digital national land information (administrative district-based data) from the Ministry of Land, Infrastructure, Transport and Tourism of Japan (https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N03-2024.html).

Table 1. Candidate crops for the four-year paddy-upland rotation systems

Crop	Fieldwork season in paddy fields[a]	
	Beginning	End
DR	Mid-March	Early October
WW	Late August of the preceding year	Late July
WWR	Early September of the preceding year	Late July
SW	Mid-March	Early August
SWE	Early October of the preceding year	Late July
SY	Mid-May	Early October
RS	Late August of the preceding year	Late July
DSB	Mid-November of the preceding year	Late October

DR: dry direct-seeded rice; WW: conventional winter wheat; WWR: winter wheat under soybean-wheat relay intercropping; SW: conventional spring wheat; SWE: spring wheat seeded in early winter; SY: soybeans; RS: rapeseed; and DSB: direct-seeded sugar beets
[a] Data sourced from SAEC (2019).

for upland crop rotation in drained paddy fields (SAEC 2019).

Table 2 provides the economic, environmental, and food security indicators of the candidate crops. These indicators, derived from data collated from the relevant literature, were used to formulate the objective functions of the multi-objective optimization problem.

The economic indicator is crop revenue (Groot & Yang 2022), calculated by multiplying the standard crop yields by the unit prices, including subsidies (DAHG 2024). Yields on upland crops were derived from the production protocols in drained paddy fields. However, yields under cultivation in upland fields were applied to SW and DSB because of a lack of data (DAHG 2024). Considering that the four-year paddy-upland rotation systems can prevent continuous cropping problems (SAEC 2019), the yield is assumed to be constant regardless of the rotation phase in which a crop is cultivated.

Nitrate nitrogen (NO_3-N) pollution of groundwater from nitrogen fertilization is a key environmental problem in Hokkaido (Nakatsuji et al. 2021), so nitrogen fertilizer inputs were selected as the environmental indicator. Table 3 shows these calculated based on

Table 2. Economic, environmental, and food security indicators of the candidate crops

		DR	WW	WWR	SW	SWE	SY	RS	DSB
Economic indicator									
Crop revenue	(yen/ha)	1,225,260	663,840	580,860	651,240	651,240	679,680	484,960	934,800
Crop yield	(kg/ha)	5,400	4,800	4,200	3,600	3,600	2,400	2,800	57,000
Price	(yen/kg)	226.9	138.3	138.3	180.9	180.9	283.2	173.2	16.4
Environmental indicator									
Fertilizer nitrogen inputs in lowland soils									
Year 1 of rotation	(kg N/ha)	66.5							
Year 2 of rotation	(kg N/ha)		86.7	66.7	60	135	95	120	140
Year 3 of rotation	(kg N/ha)		86.7	66.7	60	135	95	120	140
Year 4 of rotation	(kg N/ha)		106.7	86.7	80	155	115	140	160
Fertilizer nitrogen inputs in peat soils									
Year 1 of rotation	(kg N/ha)	42.5							
Year 2 of rotation	(kg N/ha)		66.7	46.7	40	135	95	100	120
Year 3 of rotation	(kg N/ha)		66.7	46.7	40	135	95	100	120
Year 4 of rotation	(kg N/ha)		86.7	66.7	60	155	115	120	140
Fertilizer nitrogen inputs in upland soils									
Year 1 of rotation	(kg N/ha)	60							
Year 2 of rotation	(kg N/ha)		86.7	66.7	70	135	100	120	150
Year 3 of rotation	(kg N/ha)		86.7	66.7	70	135	100	120	150
Year 4 of rotation	(kg N/ha)		106.7	86.7	90	155	120	140	170
Fertilizer nitrogen inputs in volcanic soils									
Year 1 of rotation	(kg N/ha)	77							
Year 2 of rotation	(kg N/ha)		86.7	66.7	70	135	100	120	160
Year 3 of rotation	(kg N/ha)		86.7	66.7	70	135	100	120	160
Year 4 of rotation	(kg N/ha)		106.7	86.7	90	155	120	140	180
Food security indicator									
Food calories	(kcal/ha)	18,684,000	15,792,000	13,818,000	11,844,000	11,844,000	8,928,000	6,457,360	35,478,190
Ratio of the product weight to the crop yield		100%	100%	100%	100%	100%	100%	26%	15.8%
Ratio of the edible portion to the product weight		100%	100%	100%	100%	100%	100%	100%	100%
Calories of the edible portion of the product	(kcal/kg)	3,460	3,290	3,290	3,290	3,290	3,720	8,870	3,940

DR: dry direct-seeded rice; WW: conventional winter wheat; WWR: winter wheat under soybean-wheat relay intercropping; SW: conventional spring wheat; SWE: spring wheat seeded in early winter; SY: soybeans; RS: rapeseed; and DSB: direct-seeded sugar beets

Table 3. Calculation procedure for nitrogen fertilizer inputs for the candidate crops

Crop	Definition[a]
DR	$NFIDR_j = (NFRTR_j + INCNFR) \times PCT_j$, where $NFIDR_j$ is the nitrogen fertilizer input (kg N/ha) for DR for soil type j; $NFRTR_j$ is the nitrogen fertilizer recommendation (70-95 kg N/ha) corresponding to the yield (5,400 kg/ha) of transplanted rice for soil type j; $INCNFR$ is the recommended increased amount (15 kg N/ha) of nitrogen fertilizer for rice for processing use; PCT_j is the recommended percentage (50%-70%) of nitrogen fertilizer for rice in the first year of paddy fields restored from upland fields for soil type j; and the subscript j includes dry-lowland soils, wet-lowland soils, peat soils, upland soils, and volcanic soils. The sum of $NFRTR_j$ and $INCNFR$ is assumed to be the nitrogen fertilizer recommendation for DR for soil type j (Takemoto 2021). The nitrogen fertilizer input for DR for lowland soils is a weighted average of those for dry-lowland and wet-lowland soils, weighted by the areas of these paddy soils in the Sorachi region (Hashimoto 2008).
WW	$NFIWW_k = NFRWW_k - DECWW - NFCUT$, where $NFIWW_k$ is the nitrogen fertilizer input (kg N/ha) for WW for soil type k; $NFRWW_k$ is the nitrogen fertilizer recommendation (120-140 kg N/ha) corresponding to the WW yield (5,800 kg/ha) for soil type k; $DECWW$ is the decreased amount (33.3 kg N/ha) of nitrogen fertilizer recommended based on 4,800 kg/ha of WW yield; $NFCUT$ is the amount (20 kg N/ha) of nitrogen fertilizer cut in years 2 and 3 of four-year paddy-upland rotation; and the subscript k includes lowland soils, peat soils, upland soils, and volcanic soils.
WWR	$NFIWWR_k = NFRWW_k - DECWWR - NFCUT$, where $NFIWWR_k$ is the nitrogen fertilizer input (kg N/ha) for WWR for soil type k and $DECWWR$ is the decreased amount (53.3 kg N/ha) of nitrogen fertilizer recommended based on 4,200 kg/ha of WWR yield. The nitrogen fertilizer recommendation for WWR for soil type k in HRO (2020) was not applied because of a lack of information on the number of stems in early spring (DAHG 2024).
SW	$NFISW_k = NFRSW_k - NFCUT$, where $NFISW_k$ is the nitrogen fertilizer input (kg N/ha) for SW for soil type k and $NFRSW_k$ is the nitrogen fertilizer recommendation (60-90 kg N/ha) corresponding to the SW yield (3,600 kg/ha) for soil type k.
SWE	$NFISWE = NFRSWE - NFCUT$, where $NFISWE$ is the nitrogen fertilizer input (kg N/ha) for SWE and $NFRSWE$ is the nitrogen fertilizer recommendation (155 kg N/ha) for SWE based on fertilization in early spring and at the flag leaf stage. The effects of yield levels and soil types on SWE fertilization were not considered in HRO (2020).
SY	$NFISY_k = NFRSY_k + NTDSY - NFCUT$, where $NFISY_k$ is the nitrogen fertilizer input (kg N/ha) for SY for soil type k; $NFRSY_k$ is the nitrogen fertilizer recommendation (15-20 kg N/ha) corresponding to the SY yield (2,400-3,200 kg/ha) for soil type k; and $NTDSY$ is the amount (100 kg N/ha) of nitrogen top-dressing at the flowering stage in SY production.
RS	$NFIRS_k = NFRRS_k - NFCUT$, where $NFIRS_k$ is the nitrogen fertilizer input (kg N/ha) for RS for soil type k and $NFRRS_k$ is the nitrogen fertilizer recommendation (120-140 kg N/ha) corresponding to the RS yield (3,000 kg/ha) for soil type k. Because HRO (2020) did not describe the effects of yield levels on RS fertilization, $NFRRS_k$ was not adjusted based on 2,800 kg/ha of RS yield.
DSB	$NFIDSB_k = NFRDSB_k - NFCUT$, where $NFIDSB_k$ is the nitrogen fertilizer input (kg N/ha) for DSB for soil type k and $NFRDSB_k$ is the nitrogen fertilizer recommendation (140-180 kg N/ha) corresponding to the DSB yield (60,000-70,000 kg/ha) for soil type k. Because HRO (2020) did not describe the effects of yield levels on DSB fertilization, $NFRDSB_k$ was not adjusted based on 57,000 kg/ha of DSB yield.

DR: dry direct-seeded rice; WW: conventional winter wheat; WWR: winter wheat under soybean-wheat relay intercropping; SW: conventional spring wheat; SWE: spring wheat seeded in early winter; SY: soybeans; RS: rapeseed; and DSB: direct-seeded sugar beets

[a] These calculations were based on the nitrogen fertilizer recommendations for candidate crops, assuming no application of organic materials and middle soil fertility (HRO 2020). When HRO (2020) had multiple nitrogen fertilization methods for a candidate crop, the nitrogen application procedure specified by DAHG (2024) was selected.

nitrogen fertilizer recommendations for the candidate crops (HRO 2020). As the nitrogen fertilizer recommendations are made by soil type, the effects of soil types are reflected in the environmental indicator. Other nitrogen inputs, such as biological nitrogen fixation, irrigation water, and precipitation, were excluded because it is difficult to include conditions, such as soil types, cultivation methods, and geographical locations, in the calculations. Agrochemicals are another important source of water pollution, with risks depending on the inputs of active ingredients (Masuda 2023). However, they were excluded from consideration because DAHG (2024) did not have the information (the trade names of the agrochemicals and their application rates) required for the calculations.

To express the food self-sufficiency potential, food calories were selected as the food security indicator (MAFF 2022). In addition to the crop yields (DAHG 2024), the food calories were calculated using data on ratios of the product weight to the crop yield, ratios of the edible portion to the product weight, and the calories of the edible portion of the product. The ratios of the product weight to the crop yield were 100% for DR, WW, WWR, SW, SWE, and SY (as harvested crops; MEXT 2020), 26% for RS (as rapeseed oil; TARC 2008), and 15.8% for DSB (as granulated sugar; DAHG 2020-2022, Saito

2015). The ratios of the edible portion to the product weight and calories of the edible portion of the product were sourced from the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT 2020).

3. Model formulation

Under land-use constraints, the regional optimization model incorporates economic and food security objective functions to be maximized and an environmental objective function to be minimized. The decision variable is the farmland area allocated to a crop group for a four-year paddy-upland rotation. If DR is cultivated in year 1 of the rotation, there are 343 possible combinations of three upland crops grown in years 2-4. Of these, four-year paddy-upland rotation systems with impossible crop selection and/or duplication of the same crop were excluded. Finally, eight crop groups (including 20 four-year paddy-upland rotation systems) were identified as decision variables (Table 4). WW is not chosen in any crop groups.

Table 5 presents the coefficients of the decision variables for the economic, environmental, and food

Table 4. Crop groups and four-year paddy-upland rotation systems for the decision variables

Decision variable	Crop group	Four-year paddy-upland rotation system[a]
x_1	DR, WWR, SY, and RS	DR–SY–WWR–RS rotation
x_2	DR, WWR, SY, and DSB	DR–SY–WWR–DSB and DR–DSB–SY–WWR rotations
x_3	DR, SW, SY, and RS	DR–SW–RS–SY and DR–SY–SW–RS rotations
x_4	DR, SW, SY, and DSB	DR–SW–SY–DSB, DR–SW–DSB–SY, DR–SY–SW–DSB, DR–SY–DSB–SW, DR–DSB–SW–SY, and DR–DSB–SY–SW rotations
x_5	DR, SW, RS, and DSB	DR–SW–RS–DSB and DR–DSB–SW–RS rotations
x_6	DR, SWE, SY, and RS	DR–SWE–RS–SY and DR–SY–SWE–RS rotations
x_7	DR, SWE, SY, and DSB	DR–SWE–SY–DSB, DR–SWE–DSB–SY, DR–SY–SWE–DSB, and DR–DSB–SY–SWE rotations
x_8	DR, SWE, RS, and DSB	DR–SWE–RS–DSB rotation

DR: dry direct-seeded rice; WW: conventional winter wheat; WWR: winter wheat under soybean-wheat relay intercropping; SW: conventional spring wheat; SWE: spring wheat seeded in early winter; SY: soybeans; RS: rapeseed; and DSB: direct-seeded sugar beets

[a] These systems were identified based on the following conditions. (1) Cultivation of succeeding crops was assumed to be allowed when the beginning of the fieldwork season for these succeeding crops overlapped with or followed the end period of the fieldwork season for the preceding crops (Table 1). (2) WWR was available only if the preceding crop was SY. (3) Three different upland crops were cultivated in the four-year paddy-upland rotation system. When wheat was planted, WW, WWR, SW, or SWE could be selected.

Table 5. Coefficients of the decision variables for the economic, environmental, and food security objective functions

Decision variable	Objective function[a]					
	Economic	Environmental				Food security
	All soil types (yen/ha/y)	Lowland soils (kg N/ha/y)	Peat soils (kg N/ha/y)	Upland soils (kg N/ha/y)	Volcanic soils (kg N/ha/y)	All soil types (kcal/ha/y)
x_1	742,690	92.0	76.0	91.7	95.9	11,971,840
x_2	855,150	97.0	81.0	99.2	105.9	19,227,048
x_3	760,285	90.4	74.4	92.5	96.8	11,478,340
x_4	872,745	95.4	79.4	100	106.8	18,733,548
x_5	824,065	101.6	80.6	105	111.8	18,115,888
x_6	760,285	109.1	98.1	108.8	113	11,478,340
x_7	872,745	114.1	103.1	116.3	123	18,733,548
x_8	824,065	120.4	104.4	121.3	128	18,115,888

[a] The coefficients are annual averages per unit area for four-year paddy-upland rotation. In Eq. (1), because the crop yield data on which crop revenues were calculated did not include information on soil type (DAHG 2024), the same crop revenue coefficients were used for all soil types across the multi-objective optimization problem. Similarly, the food calorie coefficients in Eq. (3) do not vary by soil type.

security objective functions. The multi-objective optimization problem is expressed as:

$$\text{Minimize} \quad -TCR_k = -\sum_{i=1}^{8} CR_{i,k}x_{i,k}, \tag{1}$$

$$\text{Minimize} \quad TNFI_k = \sum_{i=1}^{8} NFI_{i,k}x_{i,k}, \tag{2}$$

$$\text{Minimize} \quad -TFC_k = -\sum_{i=1}^{8} FC_{i,k}x_{i,k}, \tag{3}$$

subject to

$$\sum_{i=1}^{8} x_{i,k} = 1, \tag{4}$$

$$0 \leq x_{i,k} \leq 1 \ (\forall i, \forall k), \tag{5}$$

where TCR_k is the total crop revenue (yen/ha/y) for soil type k; $CR_{i,k}$ is the crop revenue coefficient (yen/ha/y) of the ith crop group for soil type k; $x_{i,k}$ is the percentage of farmland area of the ith crop group for soil type k; $TNFI_k$ is the total nitrogen fertilizer input (kg N/ha/y) for soil type k; $NFI_{i,k}$ is the nitrogen fertilizer input coefficient (kg N/ha/y) of the ith crop group for soil type k; TFC_k is the total food calories (kcal/ha/y) for soil type k; $FC_{i,k}$ is the food calorie coefficient (kcal/ha/y) of the ith crop group for soil type k; and the subscripts i and k denote the eight crop groups (Table 4) and four soil types (lowland soils, peat soils, upland soils, and volcanic soils), respectively. To convert the maximization problem into a minimization problem, Eqs (1) and (3) were multiplied by −1 (MathWorks 2024). An equal sign in Eq. (4) indicates that fallow fields were unacceptable for minimization in Eq. (2). Under the constraints of Eqs (4) and (5), an optimal solution of the decision variable was deemed the adoption rate of the crop group.

4. Multi-objective genetic algorithm

A multi-objective genetic algorithm (MOGA), which does not require the user to prioritize, scale, or weigh objectives (Konak 2006), was applied to solve the multi-objective optimization problem. A MOGA is typically used to address small-scale problems (Fu & Wen 2017). To yield Pareto-optimal solutions that cannot be improved for any objective without worsening at least one other objective, the operators of crossover (generating offspring solutions from parent solutions), mutation (mutating each solution), and reproduction (duplicating good solutions and eliminating bad solutions) were used (Deb 2001, Konak 2006). Pareto-optimal solutions form a Pareto front that provides trade-offs between the objective functions (Konak 2006).

To solve the multi-objective optimization problem, this study used the gamultiobj solver, a variant of a nondominated sorting genetic algorithm (NSGA-II) in MATLAB Version R2024a with the Global Optimization Toolbox (Deb 2001, MathWorks 2024). The solver options were not changed, but the random number generator was set to default for reproducibility. The Pareto-optimal solutions were classified by k-means clustering based on the optimal objective values, which were normalized. The statistical analyses were performed using BellCurve for Excel Version 4.07 (SSRI 2024).

Results

Table 6 presents the MOGA-based Pareto-optimal solutions by cluster in the Sorachi region. The numbers of MOGA-based Pareto-optimal solutions for lowland soils, peat soils, upland soils, and volcanic soils are 70, 70, 70, and 103, respectively (Figs. A1-A4). Based on k-means clustering, the MOGA-based Pareto-optimal solutions for each soil type were divided into three clusters: economic and food security, balanced, and environmental. For Table 6, the results by cluster are weighted averages based on the averages of the MOGA-based Pareto-optimal solutions by cluster for lowland soils, peat soils, upland soils, and volcanic soils (Table A1). The weights are the areas of the paddy fields for these soil types (Hashimoto 2008).

The average optimum values of the economic and food security cluster, the balanced cluster, and the environmental cluster were 855.8, 808.8, and 767.8 for the total crop revenue (thousand yen/ha/y), 92.4, 90.2, and 88.2 for the total nitrogen fertilizer input (kg N/ha/y), and 17.7, 15.0, and 12.5 for the total food calories (million kcal/ha/y), respectively. The total crop revenue, total nitrogen fertilizer input, and total food calories for the economic and food security cluster were 11.5%, 4.8%, and 42.0% higher, respectively, than those for the environmental cluster. The two highest adoption rates for crop groups were 83.9% of x_4 (DR, SW, SY, and DSB) and 7.7% of x_3 (DR, SW, SY, and RS) for the economic and food security cluster, 45.1% of x_4 and 32.0% of x_3 for the balanced cluster, and 55.5% of x_3 and 32.7% of x_1 (DR, WWR, SY, and RS) for the environmental cluster.

Table 6. MOGA-based Pareto-optimal solutions by cluster in the Sorachi region[a]

		EFS	BAL	ENV
Average optimum values of objective functions				
Total crop revenue	(thousand yen/ha/y)	855.8	808.8	767.8
Total nitrogen fertilizer input	(kg N/ha/y)	92.4	90.2	88.2
Total food calories	(million kcal/ha/y)	17.7	15.0	12.5
Average optimum areas of decision variables				
x_1		6.6%	21.6%	32.7%
x_2		1.5%	1.1%	0.3%
x_3		7.7%	32.0%	55.5%
x_4		83.9%	45.1%	11.4%
x_5		0.3%	0.3%	0.1%
x_6		0.0%	0.0%	0.0%
x_7		0.1%	0.1%	0.0%
x_8		0.0%	0.0%	0.0%

[a] The economic and food security, balanced, and environmental clusters are abbreviated EFS, BAL, and ENV, respectively.

Discussion

The important crop groups of x_4, x_3, and x_1, identified from the multi-objective optimization results, include DR, wheat (SW or WWR), and SY. Cultivating DSB as the fourth crop in the four-year paddy-upland rotation systems enhances crop revenues and food calories, whereas cultivating RS as the fourth crop reduces nitrogen fertilizer inputs (Table 2). There are considerable differences in both the economic and food security coefficients between x_4 including DSB and x_3 and x_1 including RS. Conversely, the environmental coefficients for x_4, including DSB, are not much different from those for x_3 and x_1 including RS (Table 5).

In the Sorachi region, 96.4% of the surveyed wells fulfilled the NO_3-N environmental standard (10 mg N/L) (Nakatsuji et al. 2021); thus, the NO_3-N pollution of groundwater from nitrogen fertilization was not considered a significant issue. Furthermore, there was little difference in total nitrogen fertilizer inputs between the economic and food security cluster (92.4 kg N/ha/y) and the environmental cluster (88.2 kg N/ha/y). On the assumption of compliance with the NO_3-N environmental standard, the economic and food security cluster results should be preferable to policymakers over other cluster results in promoting the four-year paddy-upland rotation.

An important issue for adopting the four-year paddy-upland rotation system for cultivating new crops such as DR, RS, and DSB in the Sorachi region is the introduction of agricultural machinery. Traditional rice farmers, who repeatedly produce transplanted rice in flooded paddy fields and continuously crop and rotate wheat and SY in drained paddy fields (Takemoto 2021), require a sugar beet harvester as a DSB specialized machine (SAEC 2019), although there is no need for new agricultural machines for DR and RS. The rice farmers will need to decide whether to own new agricultural machinery individually or jointly; otherwise, the farm operations must be outsourced. Budgetary measures can mitigate the rice farmers' monetary constraints regarding farm machinery.

Another important issue is ensuring labor inputs for the new crops in four-year paddy-upland rotation systems. Conversion of conventional transplanted rice (71.2-80.1 h/ha) to DR (40.3 h/ha) will significantly reduce the labor inputs for rice production (DAHG 2024). Compared with other upland crops (9.0-17.2 h/ha for wheat and 59.1 h/ha for SY), RS (22.2 h/ha) and DSB (29.0 h/ha) have moderate labor burdens (DAHG 2024). Overall, adopting four-year paddy-upland rotation systems will reduce the total labor inputs for these rice farmers (Takemoto 2021).

Conclusion

In conclusion, to prioritize enhancing crop revenues and food calories in the Sorachi region, promoting four-year paddy-upland rotation systems based on DR, SW, SY, and DSB is desirable, given the low nitrogen contamination of groundwater. Where groundwater nitrogen contamination is a concern, four-year paddy-upland rotation systems based on DR, wheat (SW or WWR), SY, and RS may be recommended. Local policymakers can refer to these findings to assist in deciding cropping systems. This paper suggests that a MOGA technique can provide decision-makers with options that consider the trade-offs between multiple objectives.

This study's limitations were caused by using data drawn from the literature. Because most data cover the entire area of Hokkaido, the multi-objective optimization problem does not fully reflect real agricultural production conditions in the Sorachi region. Further, because of insufficient information in the literature, several objective functions (e.g., minimization of agrochemical use) formulated in previous studies were excluded from the analysis. These limitations could be mitigated if a multi-objective optimization problem were formulated based on data from conducting field surveys of a sufficient number of sample farms in this region.

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Appendix. Detailed MOGA results

For more details on the MOGA results, refer to Figs. A1-A4 and Table A1.

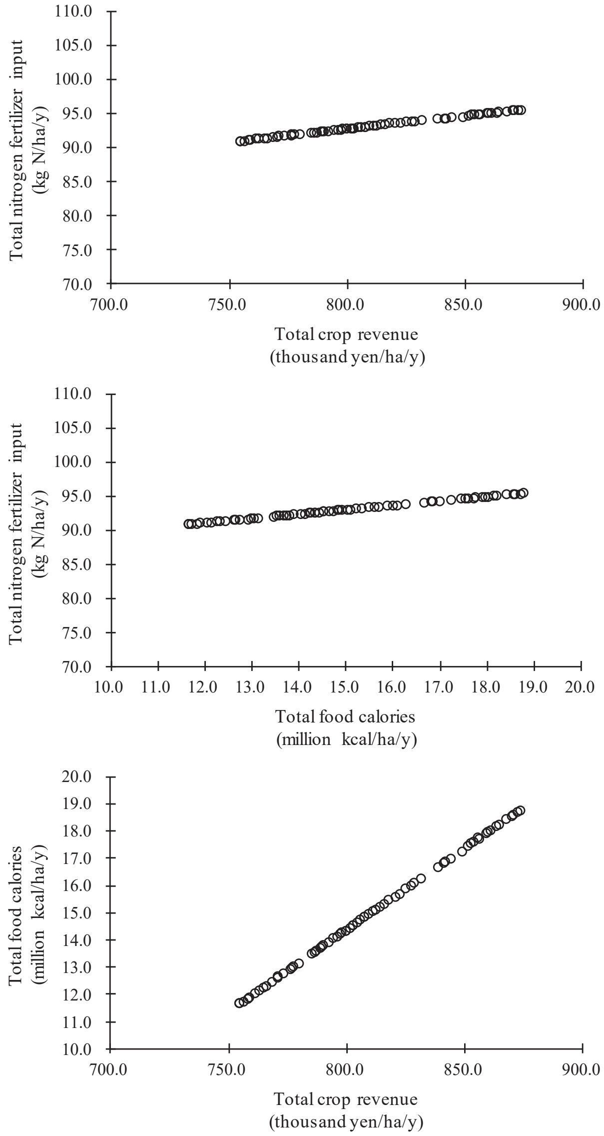

Fig. A1. Pareto fronts of the objective functions based on the MOGA results for lowland soils

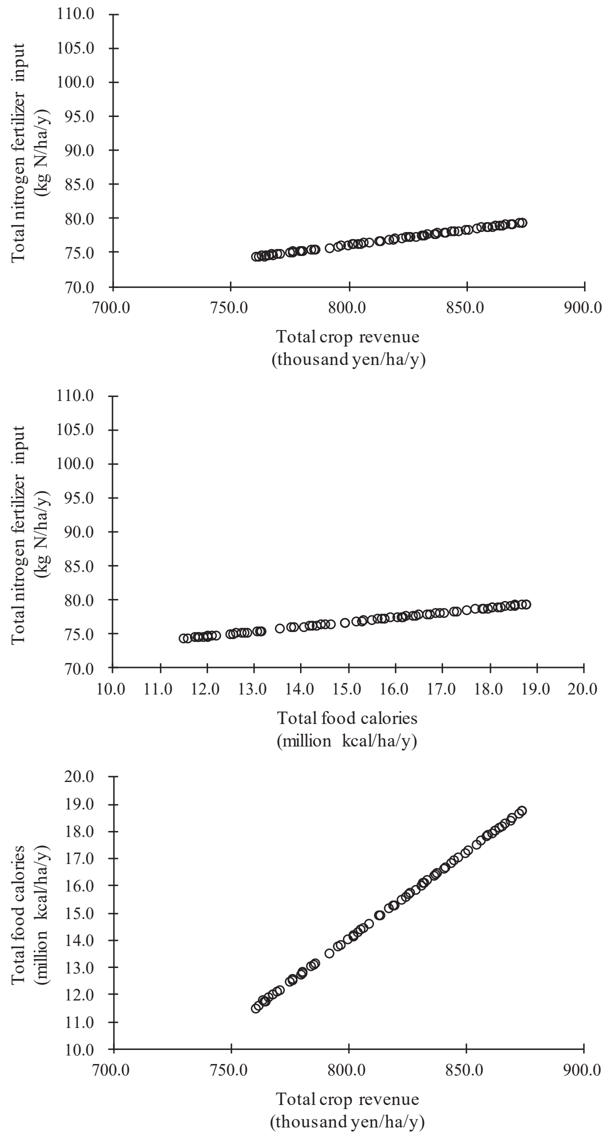

Fig. A2. Pareto fronts of the objective functions based on the MOGA results for peat soils

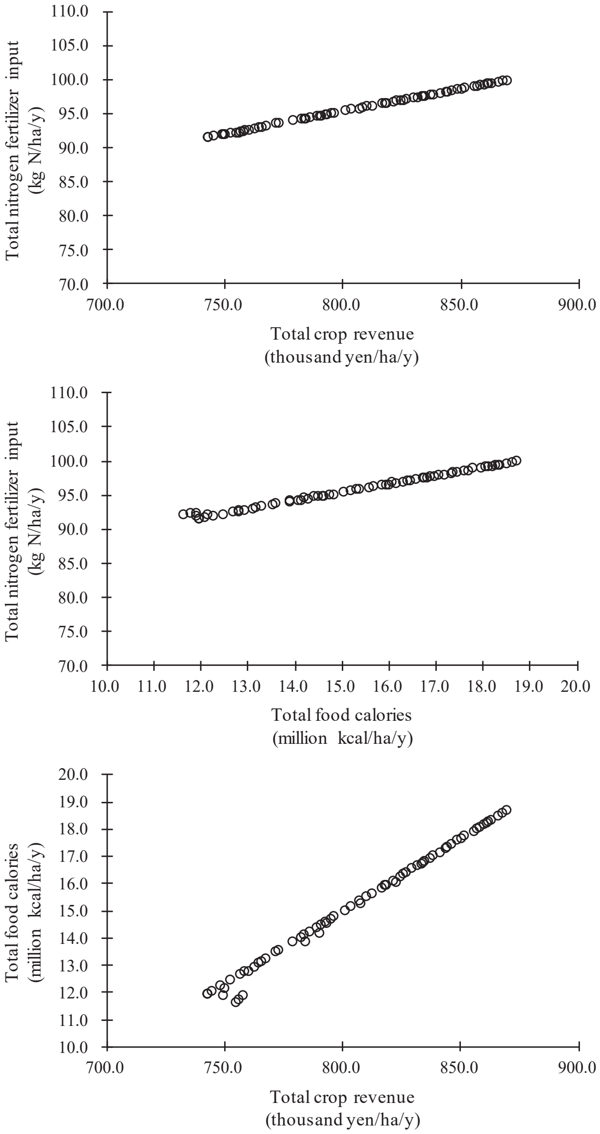

Fig. A3. Pareto fronts of the objective functions based on the MOGA results for upland soils

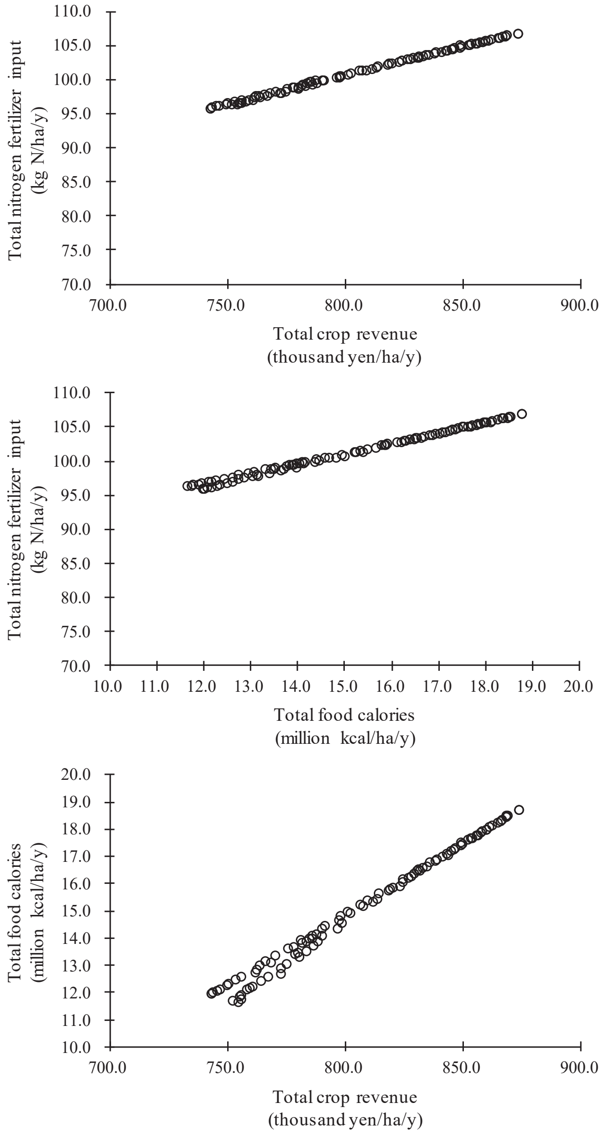

Fig. A4. Pareto fronts of the objective functions based on the MOGA results for volcanic soils

Table A1. MOGA-based Pareto-optimal solutions by cluster with respect to each soil type in the Sorachi region[a]

		Lowland soils			Peat soils			Upland soils			Volcanic soils		
		EFS (N = 20)	BAL (N = 29)	ENV (N = 21)	EFS (N = 23)	BAL (N = 25)	ENV (N = 22)	EFS (N = 27)	BAL (N = 23)	ENV (N = 20)	EFS (N = 39)	BAL (N = 30)	ENV (N = 34)
Average optimum values of objective functions													
Total crop revenue	(thousand yen/ha/y)	857.2	807.3	768.6	860.3	820.6	775.6	846.7	799.9	755.9	849.8	800.5	761.5
Total nitrogen fertilizer input	(kg N/ha/y)	94.9	93.0	91.5	78.9	77.1	75.1	98.5	95.5	92.5	104.9	100.8	97.4
Total food calories	(million kcal/ha/y)	17.8	14.8	12.5	17.9	15.4	12.5	17.5	15.0	12.5	17.5	14.8	12.6
Average optimum areas of decision variables													
x_1		4.6%	18.7%	28.8%	0.5%	1.3%	2.3%	18.4%	52.1%	78.7%	15.2%	44.7%	63.2%
x_2		0.2%	0.3%	0.1%	0.5%	0.8%	0.4%	8.5%	4.8%	1.0%	0.1%	0.2%	0.1%
x_3		9.0%	37.0%	59.4%	11.0%	45.1%	83.7%	0.5%	3.7%	12.6%	3.0%	12.3%	25.7%
x_4		86.1%	44.0%	11.7%	88.0%	52.8%	13.5%	71.0%	38.3%	7.2%	80.9%	41.5%	10.5%
x_5		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.5%	0.9%	0.4%	0.7%	1.2%	0.5%
x_6		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.0%
x_7		0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.1%	0.0%	0.1%	0.0%
x_8		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%

[a] The economic and food security, balanced, and environmental clusters are abbreviated EFS, BAL, and ENV, respectively. The sample size in each cluster represents the number of Pareto-optimal solutions.