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Optimization model for cropping-plan placement in paddy fields considering agricultural profit and nitrogen load management in Japan

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Abstract

An optimization model for cropping-plan placement on field plots is presented for supporting decision-making on agricultural management by a farming organization. The mixed 0-1 programming technique is employed to select the next planting crop at each field plot in a holistic manner. Reduction of T-N (Total Nitrogen) discharged from field plots to the downstream end of the drainage canals is expressed as an objective function of the model in order to balance an achievement of economic goal and environmental conservation. Some Japanese governmental policies on regulating rice-cropping areas and on promoting production of particular upland field crops can be formulated in the model. A computational example of cropping-plan placement on field plots managed under integrated policies is given by operating the optimization model with various weights associated with the objectives. The procured trade-off curve and corresponding patterns of cropping-plan could be useful in the decision-making by the farming organization.

Keywords Pollutant load・Optimization・Decision support・Rice

Introduction

Recent decrease of total rice consumption in Japan leads to the Japanese governmental requirement that a portion of paddy fields should be converted to upland crop fields. Promotion of domestic food production is also expressed in the policy. Additionally, controlling pollutant load discharged from paddy fields is recently recognized as a key to conserve downstream water environment. Therefore, determination of cropping strategy or cropping-plan placement in a group of field plots considering both economic and environmental goals is important. Since coordination of economic and environmental goals in the agricultural decision-making is a quite complicated issue, a systematic procedure needs to be introduced to solve the problem. Employing mathematical programming, which is a kind of optimization methods, to this multiobjective decision-making problem is expected to be useful.

Some researchers have adopted mathematical programming to investigate problems on agricultural management of land or field plots. For example, Tsuchida (1992) developed a linear programming model that can determine cultivated area for rice and double-cropping of wheat and soybeans in large fields. The objective of the model is to maximize the total agricultural income under the constraints on total planting area and working hours of the farming practices. Yagi et al. (2005) presented a mixed 0-1 programming model to locate conventional rice cropping plots and ecologically-friendly winter-flooded rice cropping plots with a single objective that maximizes the agricultural gross margin. Yagi (2006) developed a methodology to provide land management alternatives in a mountainous rural area using a mixed 0-1 programming. The model attempts to maximize the total agricultural income in the area deducted by costs representing an external diseconomy (e.g., damages from diseases and wildlife animals, low efficiency of water management, etc.) of the abandonment of farming in some fields.

However, few studies have presented optimization models that produce management alternatives where the economic achievement is balanced against the environmental one. Although the optimization model presented by Yagi et al. (2005) includes constraints on winter-flooded field plot that is effective in ecological conservation, the associated physical and biochemical mechanisms are not formulated. Khanna et al. (2003) presented an integrated framework that combines a microeconomic model and a hydrological model. The framework determines a cost-effective land retirement pattern to reduce off-site sediment loadings from fields in the United States, where the retirement of cropland is one of measures against the agricultural nonpoint pollution. Yang et al. (2003) developed an integrated economic, environmental and GIS modeling framework as an extension of the study by Khanna et al. (2003) and applied it to compare cost, acreage, location and land parcel differences between a non-uniform and uniform standard across twelve

sub-watersheds in the Illinois River Basin in the United States. Moxey and White (1994) evaluated several nitrate abatement policy instruments from a cost-effectiveness standpoint using an aggregate linear programming model to approximate producers' choice of land covers and management practices. Although studies by Khanna et al. (2003) and Yang et al. (2003) treat both economic and environmental issues in optimization considering physical pollutant transport in a large area, they are not applicable to a decision-making on crop diversification in paddy fields that are consolidated in relatively small low-land areas in Japan.

In our study, an optimization model for cropping-plan placement on consolidated field plots in Japan is developed in order to consider not only agricultural profit maximization but also nitrogen load management for environmental conservation. The two goals expressed as objective functions in the optimization model are synthesized into a single objective one using the weighting method. A demonstrative example is given to illustrate production of management alternatives on determination of planting crop at each hypothetical field plot. Environmentally conservative cropping-plan in each plot can be quantitatively examined with agricultural gross margin using the developed optimization model.

Optimization Model

A farming organization is considered which manages substantial amount of field plots (e.g., more than 20ha in total) in a lowland region. Irrigation and drainage canals in the region are assumed to be independently set for the plots as a result of farm land consolidation. Discharge from a plot is directly drained into a drainage canal since each plot is located along the drainage canal. It is also assumed that farming organization has an annual goal of yield of several crops.

The optimization model is formulated as a mixed 0-1 programming problem to determine the cropping-plan selection in each field plot in the region of interest. The selection can be represented by assigning a switching variable IX_{ij} to each plot in the model, where i and j denote plot and cropping-plan, respectively. Since each field plot can choose only one cropping-plan, the following relation, Eq. (1), needs to be satisfied in an optimal solution when j_1-th plan is chosen in i-th field plot.

$$IX_{ij} = \begin{cases} 1, & j = j_1 \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

The optimization model has two goals. One goal, f_1, is to control total nitrogen load (g/m^2/day) drained from farming plots into a downstream water body. The other goal is to improve the total agricultural gross margin (yen), which is formulated using a function f_2 below. These goals are achieved by optimizing the cropping-plan placement.

By employing the weighting method for converting the multiobjective optimization problem to a scalar one, the problem considered can be expressed as

$$\text{Minimize } f = w_1 f_1 + w_2 f_2 \tag{2}$$

where

$$f_1 = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} A_i L_j e^{-\lambda d_i} IX_{ij} \tag{3}$$

$$f_2 = -\sum_{k=1}^{N_k} \sum_{i \in \Omega_k} \sum_{j=1}^{N_j} A_i (P_{jk} - C_{jk}) IX_{ij} - S \tag{4}$$

$$w_1 + w_2 = 1 \tag{5}$$

subject to :
(i) Conditions for the switching variables of each field plot

$$IX_{ij} = 0 \text{ or } 1, \quad \forall i, j \tag{6}$$

(ii) Relations among the switching variables of each field plot

$$\sum_{j=1}^{N_j} IX_{ij} = 1, \ \forall i \tag{7}$$

(iii) Conditions for the negative deviation of the income

$$D_l^- \geq 0, \quad \forall l \tag{8}$$

$$\sum_{j=1}^{N_j} \sum_{k=1}^{N_k} \sum_{i \in \Omega_k} A_i (P_{jkl} - P_{jk}) IX_{ij} + D_l^- \geq 0, \quad \forall l \tag{9}$$

(iv) Upper limit for the average negative deviation of income

$$\frac{1}{N_l} \sum_{l=1}^{N_l} D_l^- \leq \alpha \tag{10}$$

where i is the subscript for field plot; j is the subscript for cropping-plan; IX_{ij} is the

integer decision variable for cropping-plan j selected at field plot i; w_1 and w_2 are the weight coefficients; N_i is the number of field plots; N_j is the number of cropping-plans; L_j is the unit loading factor of T-N load discharged into drainage canal from the field plot where the cropping-plan j is selected (g/m^2/day); λ is the self-purification coefficient of T-N load in drainage canals (m^{-1}); d_i is distance measured along the course of drainage canal from the outfall of the field plot i to the downstream end of the main drainage canal (m); A_i is the area of the field plot i (m^2); k is the subscript for field zones; N_k is the number of field zones; Ω_k is the subscript set of field plots in Zone k; P_{jk} is the given expected (e.g., recent five-year-average) income from the plot in Zone k following the cropping-plan j (yen/m^2); C_{jk} is the supposed production cost in plot in Zone k that takes the plan j (yen/m^2); S is the total subsidies (yen); l is the subscript for each of the past years; N_l is the number of the past years where income data are obtained; D_l^- is the sum of negative deviation of income from its average in the year l (yen); P_{jkl} is the gross income from the field plot in Zone k per area in the year l, resulting from taking the cropping-plan j (yen/m^2); α is the upper limit for the average of D_l^- (yen). It is noted that variables except IX_{ij} and D_l^- are all constants and given. In Eq. (3), decrease of TN by settlement and deoxygenation along the drainage canals is assumed to occur by following the distance-related first-order kinetics which is conventionally assumed. The value of self-purification coefficient, λ, is assumed uniform for simplicity in this study. The branch-and-bound method is adopted to solve the mixed 0-1 programming problem.

Demonstrative Example

Application to field plots in Japan

In field plots that a group farming organization owns, the following farming practices for the crops are assumed to be standardized: (1) Rice seedlings are transplanted in May, and the crop is harvested in September; (2) Seeds of wheat are sown in November, and the crop

is harvested in next June; (3) Soybeans are sown in June and the crop is harvested in November. Note that soybeans can be sown after wheat is cultivated in a field plot. Although all the field plots had been developed for rice planting, some plots, whose total area is obligatory allotted by the Government to the farming organization, are set aside for planting other plants, i.e., wheat and soybeans. Since environmental pollution caused by agricultural discharges is a great concern for the organization, as well as its total profit, an environmentally- and economically-sound cropping-plan is required. Therefore, the optimization model is used to design a plan that determines which crop(s) should be planted in each plot after this November.

It is assumed that the group farming organization can select one of the four plans, listed in Table 1, for each field plot. For example, in a plot of interest, the plan 'P1' means that rice was planted this year, and rice seedlings will be transplanted next April. The plan 'P2' means that rice was planted in the plot this year, but seeds of wheat will be sown right after harvesting of rice, and then soybeans will be planted next June just after harvesting of wheat. The plans 'P3' and 'P4' shown in Table 1 are defined similarly. By solving the optimization model, the selection of a plan 'P1', 'P2', 'P3' or 'P4' is conducted with the

associated switching variable IX_{ij} (j = 1, 2, 3 and 4) for each field plot i, respectively.

Some site-specific constraints concerning the farming practice are added to the optimization model. Relations among the switching variables of each field plot according to the lastly-planted crop are introduced as shown below.

$$\sum_{j\in\{1,2\}} IX_{ij} = 1, \quad \forall i \in \Omega^r \qquad (11)$$

$$\sum_{j\in\{3,4\}} IX_{ij} = 1, \quad \forall i \in \Omega^c \qquad (12)$$

where Ω^r and Ω^c are the subscript sets of field plots where lastly-planted crop are rice (P1 and P2) and soybeans (P3 and P4), respectively. Lower limit for the rate of areas of upland fields converted from paddy fields (employing plans P2 and P4) to the total area is also formulated as

$$\sum_{i=1}^{N_i} \sum_{j\in\{2,4\}} A_i IX_{ij} \bigg/ \sum_{i=1}^{N_i} A_i \geq \frac{\beta}{100} \qquad (13)$$

where β is the lower limit for the rate of total area of upland crop fields to the total area of whole plots in the next stage (%).

The optimization model is applied to hypothetical 80 field plots in Japan where a group farming organization can choose plans listed in Table 1 for each plot with two goals represented in the objective functions. The field plots and related drainage canals are

depicted in Fig. 1. The typical size of the plot in Japan (100m by 30m) is assumed and area of all the plots is 24ha in total. Five-year incomes per unit area given in Table 2 are prepared for this computational example. Values of P_{jkl} $(j=1,3)$ in Table 2 are assumed based on the statistics of gross margin (net sales revenue) per unit area of rice cropping except in Hokkaido Prefecture from 2002 to 2006, released by Cabinet Secretariat Statistics Department of MAFF of Japan (2007). Values of P_{jkl} $(j=2,4)$ in Table 2 are the same kind of data for wheat and soybeans (Cabinet Secretariat Statistics Department of MAFF of Japan (2007)). In Table 2, values of P_{3kl} $(l=1,2,\cdots,5)$ are greater than values of P_{1kl} $(l=1,2,\cdots,5)$, which is consistent with the data observed in the fields in Niigata (Tsuchida, 2003), that is, unit yield of rice in the plot following P3 is greater than that in the plot which adopts P1. Material costs in Table 4 are substituted for production costs in the model in this example since current production costs of rice often exceed sales revenues, which do not contain the subsidy, in Japan. The values of C_{jk} $(j=1,3)$ in Table 4 are given based on a material cost per unit area of rice cropping except in Hokkaido Prefecture in 2007 (Cabinet Secretariat Statistics Department of MAFF of Japan (2008)) and C_{jk} $(j=2,4)$ are given based on the same kind data for wheat and soybeans cropping (Cabinet Secretariat Statistics Department of MAFF of Japan (2008)). Expected incomes per unit area, P_{jk} , are given as average value of P_{jkl} $(l=1,2,\cdots,5)$, as indicated in Table 3. Cost of fertilizer is reduced by employing P3 compared with P1, which results in lower material costs of C_{3k} in Table 4. Unit loading factors, the self-purification coefficient of T-N load and other parameters are shown in Table 5. Unit loading factors are determined based on Life Circumstance Department's Kasumigaura Lake Management Division of Ibaraki Prefecture (2001). The self-purification coefficient and the other parameters are assigned as reasonable values in Table 5.

Agricultural Policy

According to the approved budget for 2010 in Japan (the Japanese Government (2009)), the Ministry of Agriculture, Forestry and Fisheries (MAFF) starts projects for the direct

payments to particular farmers and farming organizations (the Ministry of Agriculture, Forestry and Fisheries (2009)).   In this study, the following principal projects (Project-1 through -3) are mentioned to consider in the optimization model.

Project-1: The direct financial support project to increase food self-sufficiency by promoting planting particular crops

The government gives direct payments to commercial farm households which convert paddy fields into multi-purpose ones and produce particular crops (e.g., barley, wheat, soybeans, rice given to animals or used as biofuel, etc.) in order to improve the self-sufficiency of food in Japan. Since the selling price of those crops is lower than that of rice in general, the subsidy is expected to compensate for the decrease of income caused by planting the crops other than rice in the fields.

Project-2: The direct financial support project to increase food self-sufficiency for rice

The government offers direct payments to commercial farm households and group farming organizations which follow the rice production adjustment program. The income compensation is composed of fixed and variable parts. Thus they can receive at least 15 yen per $1m^2$ (paddy field) as the fixed payment. If a current year's wholesale price of rice is lower than a standard price (average price in the past three years), the variable part (yen per $1m^2$) compensates for the loss of selling. It is noted that the payment rate is applied to upper portion of the area greater than $1,000m^2$.

Project 3: The compensation project for less favored farming conditions

The compensation project for less favored farming conditions offers two subsidies, one of which is determined from planted area in the past years and the other is from current year's yield and its quality. The objective crops are barley, wheat and soybeans. Farmers and group farming organizations need to satisfy some managerial requirements in order to receive the subsidies.

Formulation of subsidies

The subsidies of the Projects-1, 2 and 3 are expressed as S_1, S_2 and S_3 in Eqs. (15)-(17), respectively. The variable part of subsidy in Project-2 is not formulated. Thus S in the

second objective function Eq. (4) can be computed as a sum of S1, S2 and S3, shown in Eq. (14).

$$S = S_1 + S_2 + S_3 \qquad (14)$$

$$S_1 = s_1 \sum_{i=1}^{N_i} \sum_{j=\{2,4\}} A_i IX_{ij} \qquad (15)$$

$$S_2 = s_2 \left\{ \sum_{i=1}^{N_i} \sum_{j=\{1,3\}} A_i IX_{ij} - 1000 N_h \right\} \quad (\text{if } \sum_{i=1}^{N_i} \sum_{j=\{1,3\}} A_i IX_{ij} - 1000 N_h > 1000 N_h) \quad (16)$$

$$S_3 = \sum_{k=1}^{N_k} \sum_{i \in \Omega_k} A_i \left\{ IX_{i2} (s_3^W \overline{Y}_k^{rW} + s_3^S \overline{Y}_k^{rS}) + IX_{i4} (s_3^W \overline{Y}_k^{cW} + s_3^S \overline{Y}_k^{cS}) \right\} + A^{s_3} (s_3^w + s_3^s) \qquad (17)$$

where s_1 and s_2 are the subsidies per unit area of the Project-1 and 2 (yen/m^2), respectively; N_h is the number of families which join the farming organization; s_3^W and s_3^S are the subsidies of Project-3 based on qualitative and quantitative standards of wheat and soybeans (yen/kg), respectively; s_3^w and s_3^s are the subsidies of Project-3 based on the area where wheat and soybeans were cropped in the past years (yen/m^2), respectively; $\overline{Y}_k^{rW}$ and $\overline{Y}_k^{rS}$ are the expected yields of wheat and soybeans at the field plots in Zone k where rice was lastly cropped (kg/m^2), respectively; $\overline{Y}_k^{cW}$ and $\overline{Y}_k^{cS}$ are the expected yields of wheat and soybeans at the field plots in Zone k where crops were lastly harvested (kg/m^2), respectively; A^{s_3} is the area of field plots where multi-cropping have been conducted in the past years and the subsidy in Project-3 is determined (m^2). Coefficients regarding the subsidies are assigned referring to the Japanese Government (2009) and the Ministry of Agriculture, Forestry and Fisheries (2009) and summarized in Table 6.

Results and Discussion

The FORTRAN code developed by Ibaraki (Ibaraki and Fukushima, 1991) is used to solve the problem [Eqs. (2)-(17)]. Since the optimization model is a bi-objective programming problem, drawing the trade-off curve between objectives is meaningful by procuring noninferior solutions with various weight values of w_1 and w_2. Fig. 2 shows the trade-off relation between the discharged pollutant load from the total field plots and the total

expected gross margin in the farming organization. Fig. 3 shows various procured optimal placement of the cropping-plans to the plots. Fig. 4 represents the relation among optimal objective values and given weights. Regarding w_1 smaller than 0.900, the same optimal plan placement and objective values as those with $w_1 = 0.900$ shown in Figs. 3 and 4 is obtained.

As shown in Fig. 2, the expected gross margin is proportional to the discharged pollutant load. However, the gradient of the trade-off curve fitted to the plots in this figure varies over the range of discharged load shown in the horizontal axis. For example, when w_1 decreases from 1.0 to around 0.985, even though the pollutant load remains almost the same, the expected gross margin increased more than 0.3 million yen (see Figs. 2 and 4). This is attributed to the fact that more number of plots that employ P2 are arranged to Zones 2 and 4 where the profit values of P_{2kl} $(k = 2,4; \ l = 1,2,\cdots,5)$ are large compared with P_{2kl} $(k = 1,3; \ l = 1,2,\cdots,5)$ for Zones 1 and 3 (see Table 2 and (i)-(l) in Fig. 3).

On the other hand, the small gradient of the right part of the curve in Fig. 2 indicates that decrease of pollutant load less affects decrease of the gross margin. Therefore, the cropping-plans appearing around the right part of the trade-off curve (corresponding plans are shown in (a) and (b) in Fig. 3) may be favored by decision-makers who insist the economic achievement.

The optimal cropping-plan placement shown in Fig. 3 is certainly affected by many factors such as plot-based income and material costs, unit loading factor, flow length of discharged load from the plot to the downstream end of the drainage canal, etc. However, some tendencies can be observed in the twelve allocations in Fig. 3. As can be expected from Eqs. (2)-(4), giving larger values to w_1 emphasizes the objective f_1, i.e., minimization of the total discharged load from the plots. Since unit loading factors of paddy field in the next stage, L_1 and L_2, are smaller than those of upland crop field, shown in Table 5, the more close to 1 w_1 becomes among the noninferior solutions, the more plots where rice is planted (or 'white rectangle' in Fig. 3) appear. As w_1 increases from 0.900 to 0.964 ((a) through (e) in Fig. 3), only plots whose lastly planted crop is soybeans are sequentially selected to adopt the plan P3. This is because changing crops from soybeans-wheat to rice is the most cost-effective for the pollutant load reduction as shown in Tables 2, 3 and 5. Moreover, plots in Zone 3 is firstly chosen as w_1 increases in the range of 0.900 through 0.964, which is mainly due to the fact that $P_{3k} - C_{3k} (k=3)$ has the maximum among $P_{3k} - C_{3k} (k=1,2,3 \text{ and } 4)$. Using the obtained trade-off relation and the concrete plan placement, the farming organization could determine cropping strategies more rationally.

The trade-off relation shown in Figs. 2 and 4 provides a decision-maker of the farming

organization with meaningful information for selecting one of the solutions with various

weight values of w_1 and w_2. If the decision-maker is environmentally conscious, the

solution with as large weight value of w_1 as possible would be selected by the

decision-maker, who also considers the total expected gross margin indicated in Figs. 2 and

4. It is adequate from an environmental impact perspective to select the solution with as

large weight value of w_1 as possible or the maximum value ($w_1 = 1$). However, the

decision-maker who emphasizes economic efficiency would select normally the solution

with the minimum weigh value of w_1 and expect the maximum total gross margin. When

environmental conservation should be considered, the decision-maker would choose the

solution with the acceptable weight value of w_1 evaluating a decrease of the total expected

gross margin represented in Figs. 2 and 4. Thus, the optimization model could serve as a

management decision-making support tool for various decision makers of farming

organization which place an emphasis on environmental conservation or economic

efficiency.

Conclusions

An optimization model is developed for cropping-plan placement on the paddy field plots

that a group farming organization manages in a small low-land region in Japan. The

optimization model, formulated as a mixed 0-1 programming problem, aids to choose the

best cropping-plan at each field plot, based on economic and environmental goals. Pollutant

load discharged from the plots to the downstream can be controlled by minimization of the

first objective function representing the distance-related self-purification in the drainage

canals. The optimization model is applied to a hypothetical agricultural field containing 80

field plots. The current Japanese governmental policies for increasing food production are

expressed in the terms on subsidies and the constraint that limits the area where rice can be

cropped. The curve of trade-off between the total expected gross margin and total

discharged pollutant load is depicted by operating the optimization model in order to

explore more effective selection of cropping-plan, or management alternative in the

decision-making process.

Decision-make's preference to the two goals assumed in this study would be reflected in the selection of the management alternative when the optimization model is applied to a real existing farming organization. The cost–effectiveness indicated by the trade-off curve would practically be useful in choosing a solution which places an emphasis on environment conservation or economic efficiency by following decision-maker's preference. Since the conflict between the economic goal and pollutant load reduction in agriculture is a worldwide problem, the framework presented in this paper would be extended to applications in many low-land agricultural regions in other countries.

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Figure Caption

Fig. 1 Hypothetical field plots and drainage canals

Fig. 2 Trade-off curve between total discharged pollutant load and total expected gross margin

Fig. 3 Optimal placement of the cropping-plans on field plots computed with various values of w_1

Fig. 4 Relations among optimal objective values and w_1

Fig. 1

Field plot where soybeans were lastly planted

Field plot where rice was lastly planted

1, 2, 3, 4   Zone number

Drainage canal

▼   Downstream end of main drainage canal

→   Flow direction

0   50   100 m

Fig. 2

Fig. 3

P1   P2   P3   P4

(a) $w_1 = 0.900$ (b) $w_1 = 0.927$ (c) $w_1 = 0.936$ (d) $w_1 = 0.960$

(e) $w_1 = 0.964$ (f) $w_1 = 0.971$ (g) $w_1 = 0.972$ (h) $w_1 = 0.973$

(i) $w_1 = 0.979$ (j) $w_1 = 0.988$ (k) $w_1 = 0.999$ (l) $w_1 = 1.00$
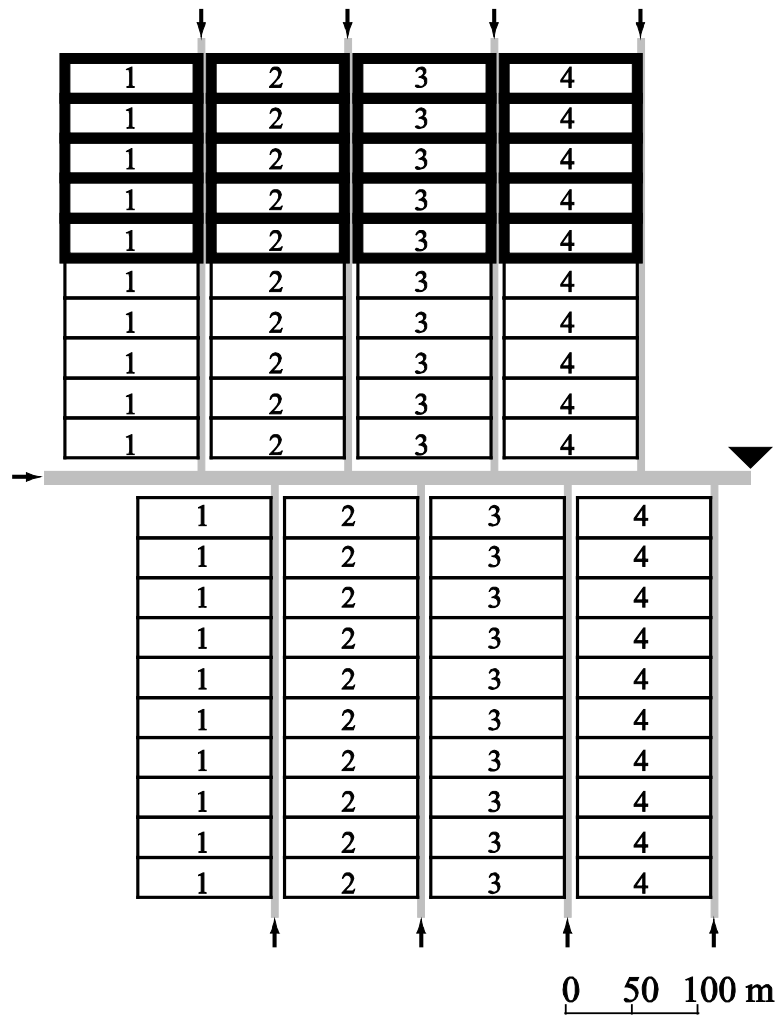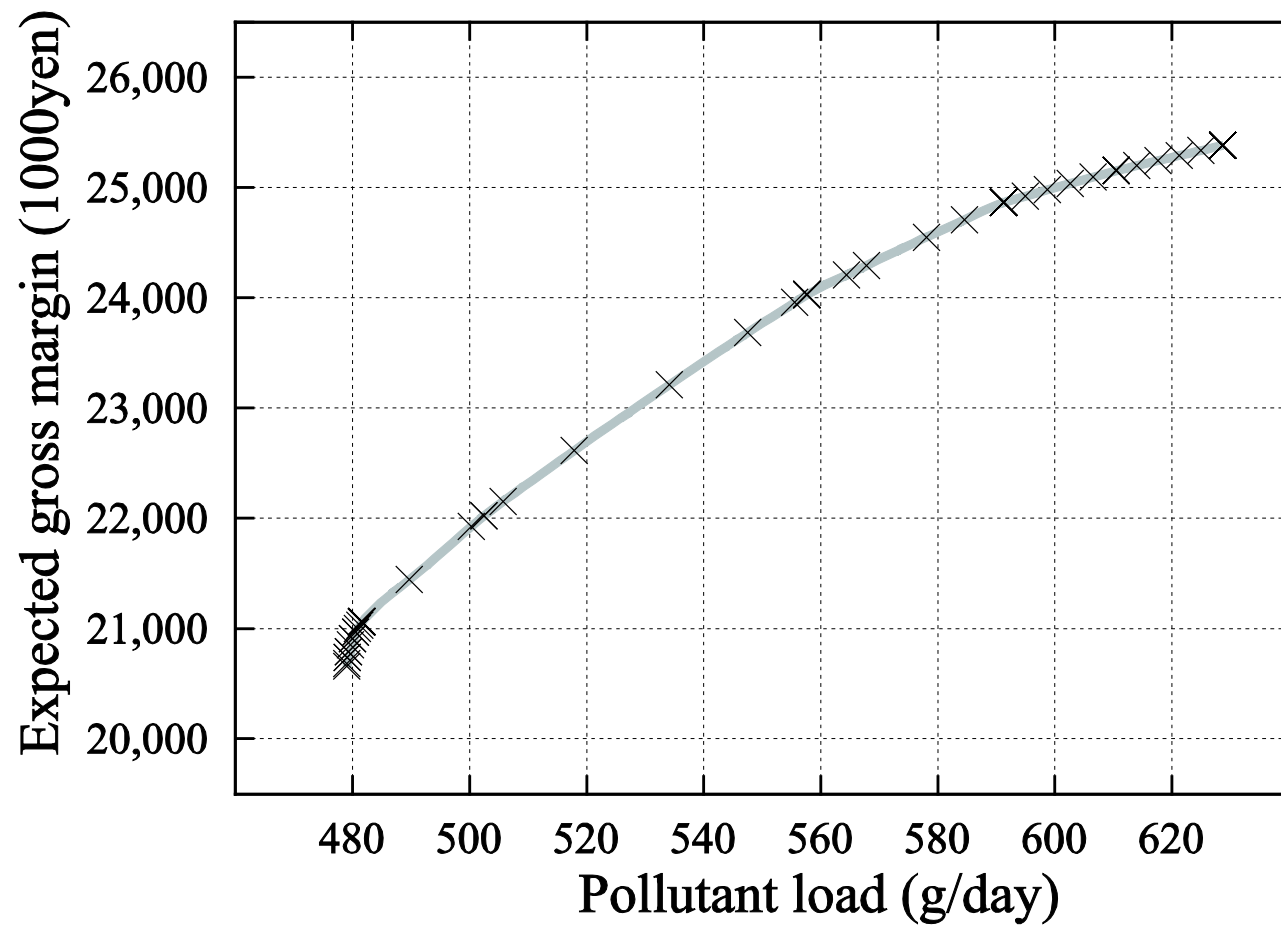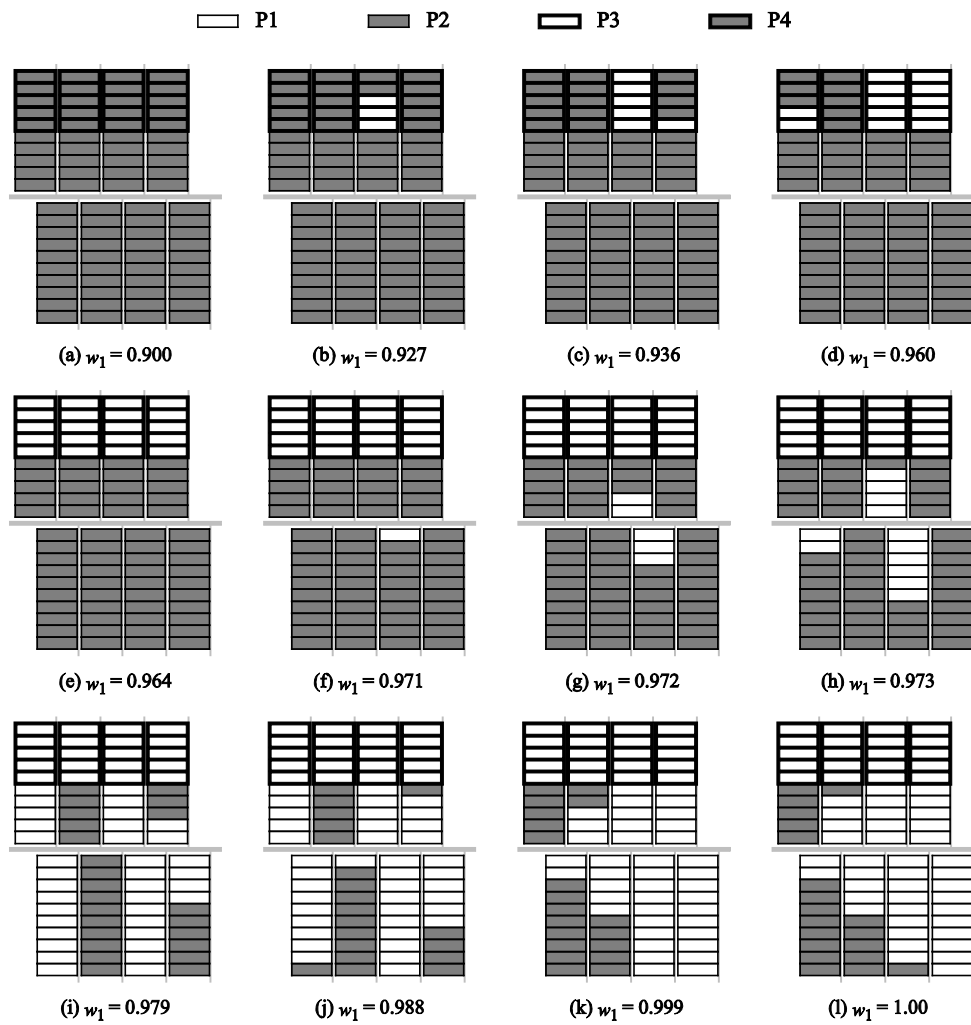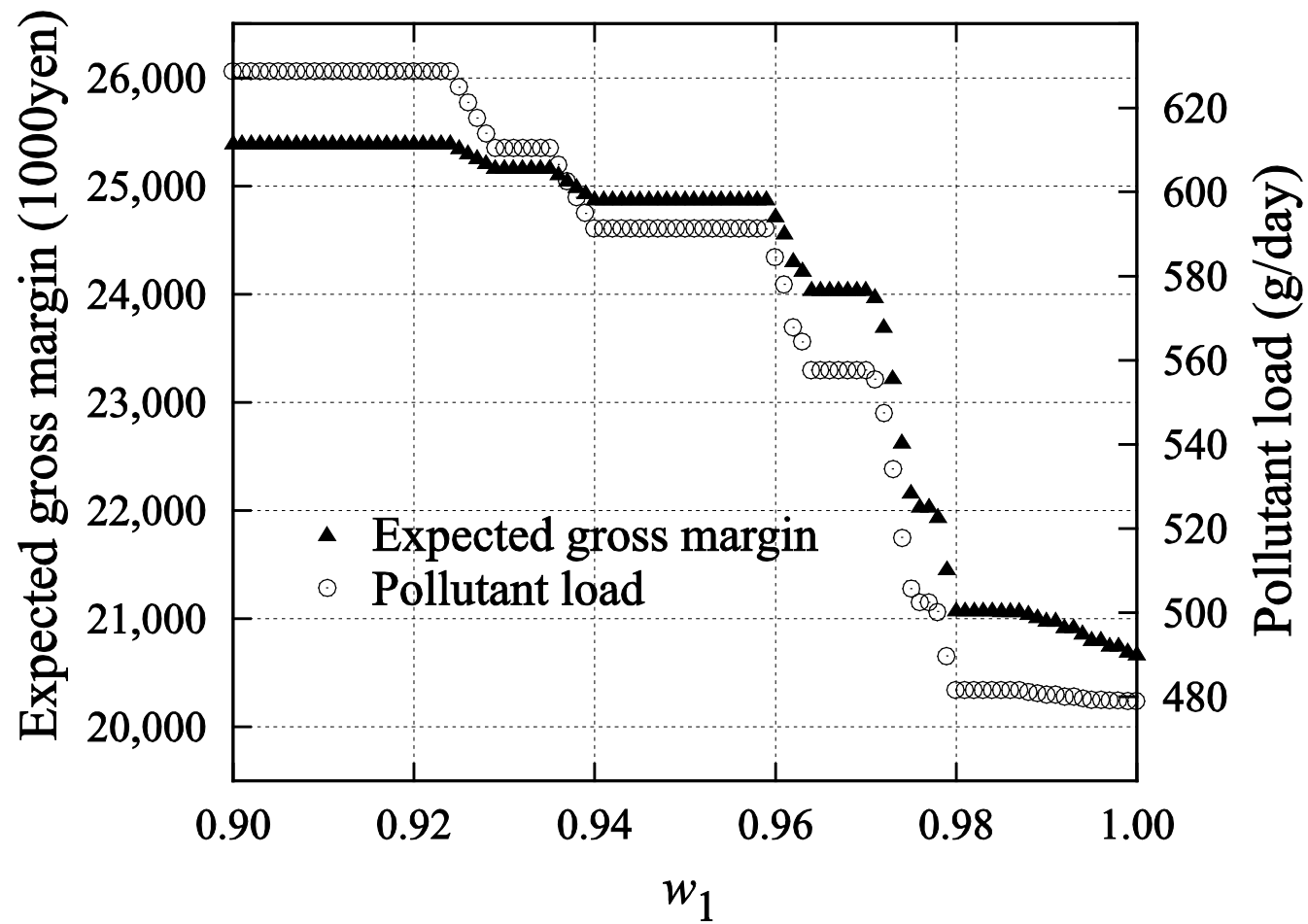
Fig. 4

Table 1 Plans for planting crops in the next stage and associated zero-one decision variables

Plan	Lastly planted (up to this November)	Planted next	Subscript j of IX_{ij}
P1	Rice	Rice	1
P2	Rice	Wheat - soybeans	2
P3	Soybeans	Rice	3
P4	Soybeans	Wheat - soybeans	4

Table 2   Unit five-year income per area

$$P_{jkl} \text{ (yen/m}^2)$$

j	l	k			
		1	2	3	4
1	1	126.914	118.245	130.554	129.069
	2	150.373	145.933	162.753	148.915
	3	119.425	114.676	122.63	117.281
	4	117.299	118.349	118.94	110.933
	5	113.415	110.293	109.379	119.055
2	1	86.769	95.582	83.206	99.967
	2	90.175	93.872	99.76	96.767
	3	97.785	95.078	86.087	98.814
	4	87.791	93.847	100.639	110.165
	5	79.986	80.795	88.408	77.711
3	1	134.648	130.53	142.598	139.39
	2	156.207	149.887	177.142	152.933
	3	132.428	133.166	132.128	117.719
	4	118.437	121.127	122.746	117.605
	5	111.542	103.404	119.858	123.024
4	1	88.587	83.727	94.038	90.927
	2	103.495	107.706	87.61	84.494
	3	81.308	92.424	86.256	87.154
	4	88.548	90.671	86.69	81.794
	5	98.706	89.343	90.168	83.651

Source: Cabinet Secretariat Statistics Department of MAFF of Japan (2007)

Table 3   Unit expected income per area

$$P_{jk} \text{ (yen/m}^2\text{)}$$

j	k			
	1	2	3	4
1	125.485	121.499	128.851	125.051
2	88.501	91.835	91.62	96.685
3	130.652	127.623	138.894	130.134
4	92.129	92.774	88.952	85.604

Table 4 Unit material costs per area

$$C_{jk} \text{ (yen/m}^2\text{)}$$

j	k
	1, 2, 3, 4
1	75.183
2	72.130
3	69.161
4	61.905

Source: Cabinet Secretariat Statistics Department of MAFF of Japan (2008)

Table 5 Other parameters

L_1 (mg/m^2/day)[a]	2.24
L_2 (mg/m^2/day)[a]	2.24
L_3 (mg/m^2/day)[a]	2.99
L_4 (mg/m^2/day)[a]	3.75
λ (m^{-1})	0.0005
N_h	4
α (yen)	1,500,000
β (%)	25.0

[a] Source: Life Circumstance Department's Kasumigaura Lake Management Division of Ibaraki Prefecture (2001)

Table 6 Subsidy rates

s_1 (yen/m^2)	50.00
s_2 (yen/ m^2)	15.00
s_3^W (yen/kg)	35.17
s_3^S (yen/kg)	45.60
s_3^w (yen/m^2)	27.74
s_3^s (yen/m^2)	20.23

Source: The Japanese Government (2009)