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Development and Evaluation of a Simulation Model for Dairy Cattle Production Systems Integrated with Forage Crop Production

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ABSTRACT : Crop-livestock mixed farming systems depend on the efficiency with which nutrients are conserved and recycled. Home-grown forage is used as animal feed and animal excretions are applied to cultivated crop lands as manure. The objective of this study was to develop a mixed farming system model for dairy cattle in Japan The model consisted of four sub-models: the nutrient requirement model, based on the Japanese Feeding Standards to determine requirements for energy, crude protein, dry matter intake, calcium, phosphorus and vitamin A; the optimum diet formulation model for determining the optimum diets that satisfy nutrient requirements at lowest cost, using linear programming; the herd dynamic model to calculate the numbers of cows in each reproductive cycle; and the whole farm optimization model to evaluate whole farm management from economic and environmental viewpoints and to optimize strategies for the target farm or system. To examine the model's validity, its predictions were compared against best practices for dairy farm management. Sensitivity analyses indicated that higher yielding cows lead to better economic results but higher emvironmental load in dairy cattle systems integrated with forage crop production. (**Key Words :** Crop-livestock Mixed Farming System, Dairy Cattle, Linear Programming, Farm Management, Simulation Model, Whole Farm)

INTRODUCTION

In Japan, increased inputs of chemical fertilizer and purchased feeds to enhance the economic efficiency of limited amounts of land have intensified dairy production in the past several decades. This trend has created imbalances of nitrogen (N) and phosphorus (P) and thus serious environmental problems. To solve these environmental problems, new laws requiring the proper management of animal excretions and promoting their use as manure were completely implemented in November, 2005.

Recycling of manure nutrients has been the most popular means to address the problem of nutrient imbalance. However, a number of difficulties prevent the effective reuse of N and P in manure: inadequate transportation systems, a shortage of farming area for manure application, and manure's low effectiveness as fertilizer. Consequently, dairy farmers face a new challenge: to simultaneously increase economic efficiency and decrease environmental loads.

A comprehensive approach that integrates dairy production, crop production, feeding and the handling of manure is needed to properly evaluate dairy producer's options for economic and environmental management (Tamminga, 1992; Rotz et al., 1999a). Normative modeling approach at farm level is one way to determine the effects of management measures on the environment (Berentsen and Tiessink, 2003). Many trials have been conducted to support dairy producers in their nutrient and farm management decision-making. Linear programming (LP) has been used to determine least-cost rations and optimal strategies for formulating rations (Henry et al., 1995; Tedeschi et al., 2000). Furthermore, computer simulation with environmental-economic models at the farm level provide a useful tool for integrating knowledge and information to predict production efficiency, environmental impacts, and the effects of management policies on production performance (Berentsen and Giesen, 1995; Berentsen, 1999; Herrero et al., 1999; Rotz et al., 1999a; Thornton and Herrero, 2001; Van Calker et al., 2004).

The objective of this study was to develop an environmental-economic model for integrated dairy systems with crop production in Japan while minimizing feed costs. Optimal farming systems based on nutrient recycling were chosen for whole farm management with least-cost ration

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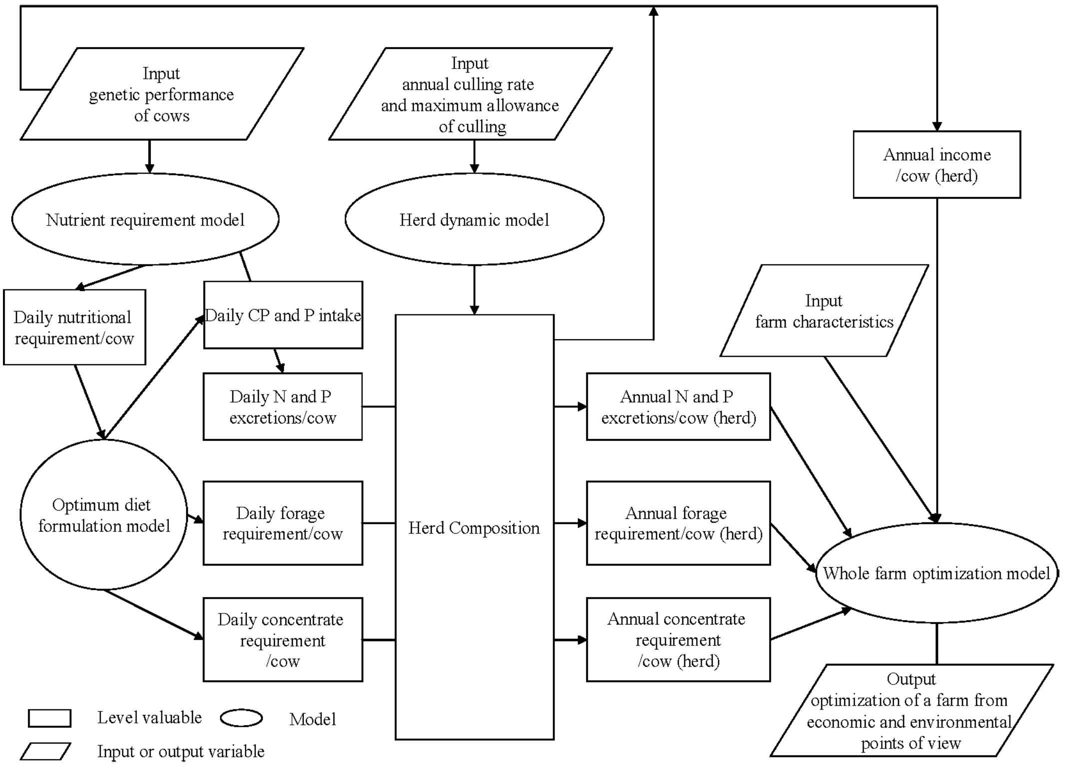

Figure 1. Overview of the present model.

calculations.

MATERIALS AND METHODS

Overview of the present model

An overview of the model structure is illustrated in Figure 1. The model consists of four sub-models: nutrient requirement model, optimum diet formulation model, herd dynamic model, and whole farm optimization model.

The nutrient requirement model was constructed based on the Japanese Feeding Standards for dairy cattle (MAFF, 1999) and used to predict metabolizable energy requirements (ME), crude protein (CP), dry matter intake (DMI), calcium (Ca), phosphorus (P) and vitamin A (VA). In addition, excretions for nitrogen (N) and P were also calculated in this model.

The optimum diet formulation model determined the optimum diet that meets nutrient requirements for the lowest cost using linear programming.

The herd dynamic model calculated the number of cows in each reproductive cycle at equilibrium. In this model, all cows with reproduction failures were assumed to be culled at the end of lactation.

The whole farm optimization model integrated outputs from the first three sub-models and determined the effects of animal performance and management policies on farm behaviors, production efficiencies, and nutrient losses to the environment. The objective function maximized in this sub-model was net profit and the elements were dairy cows, feed production, purchased fertilizer, labor, and surpluses of nitrogen and phosphorus. The production costs of home-grown feed were assumed in this model.

The present model is flexible and can be applied to various dairy cattle production systems integrated with forage crop production in Japan by changing input variables related to dairy and crop production such as genotype, nutrition, management and economic variables of dairy production, and varieties and acreage of forage crops.

Nutrient requirement model

Table 1 shows the values and equations for estimating energy and nutrient requirements based on Japanese Feeding Standards for dairy cattle (MAFF, 1999). Energy requirements of animals and some of the events in animal life were estimated based on growth curves. A growth curve was determined from three animal traits: birth weight (BW), weaning weight (WW), and mature weight (MW) (Table 1). It was also assumed that the growth curve was represented by a straight line from birth (43 kg) to weaning (98 kg) and subsequently from weaning (98 kg) to culling by a Brody curve (Brody, 1945; Kahn, 1982).

The ME requirement for lactation (ME_l) was estimated from a lactation curve. The lactation curve for a cow was determined with the integration of biological traits and the

Table 1. Values* for life cycle of dairy cattle and equations* to estimate energy and nutrient requirements quoted from Japanese Feeding Standard for Dairy Cattle

Eq.	Variable	Constraint	Equation or value	Unit
1	mo		30.4 days (length of a month)	
2	t		days of age	
3	Tp		days in pregnancy	
4	$prete$		280 days (pregnancy period)	
5	$lacte$		359 days (lactation period)	
6	MY		milk yield	kg/d
7	M_{fat}		fat content in milk	%
8	FCM		$(15.0\times M_{fat}/100.0+0.4)\times MY$	kg/d
9	W		live weight	kg
10	DG		live weight gain	kg/d
11	BW		43 kg (birth weight)	
12	WW		98 kg (weaning weight)	
13	MW		690 kg (mature weight)	
14	DMI		$DMI_{mg}+DMI_{p}+DMI_{l}$	kg/d
15	ME		$ME_{mg}+ME_{p}+ME_{l}$	Mcal/d
16	CP		$CP_{mg}+CP_{p}+CP_{l}$	g/d
17	P		$P_{mg}+P_{p}+P_{l}$	g/d
18	Ca		$Ca_{mg}+Ca_{p}+Ca_{l}$	g/d
19	VA		$VA_{mg}+VA_{p}+VA_{l}$	g/d
20	CPi		CP intake	g/d
21	Pi		P intake	g/d
22	W	<3 month age	$BW+(WW-BW)\times((t/mo)/3)$	kg
23	W	<20 month age	$22.5\times((t/mo-3)+WW$	kg
24	W	>20 month age	$MW\times(1-0.98268\times exp^{(-0.0587258\times(t/mo))})$	kg
25	DG	<3 month age	$(WW-BW)/(3\times mo)$	kg/d
26	DG	<20 month age	$22.5/mo$	kg/d
27	DG	>20 month age	$0.058725\times(MW-W)/mo$	kg/d
28	DMI_{mg}	W<45	4.5×0.12	kg/d
29	DMI_{mg}	45≤W<66	$4.5\times0.12+((0.1183\times W^{0.75}+0.1205\times DG\times W^{0.75})-4.5\times0.58)/3.15$	kg/d
30	DMI_{mg}	before lst calving	$0.49137+0.01768\times W+0.91754\times DG$	kg/d
31	DMI_{mg}	after 1st calving	$1.5+0.01\times W$	kg/d
32	DMI_{p}	9-4 weeks before calving	$5.13/2.28$	kg/d
33	DMI_{p}	3-0 weeks before calving	$6.85/2.42$	kg/d
34	DMI_{l}		$2.98120+0.00905\times W+0.41055\times FCM$	kg/d
35	ME_{mg}	W<66	$(0.1152\times W^{0.75}+0.1205\times DG\times W^{0.75})\times1.1$	Mcal/d
36	ME_{mg}	66≤W<120	$(0.1152\times W^{0.75}+0.1293\times DG\times W^{0.75})\times1.1$	Mcal/d
37	ME_{mg}	before lst calving	$(0.1152\times W^{0.75}+0.1355\times DG\times W^{0.75})\times1.07$	Mcal/d
38	ME_{mg}	after 1st calving	$0.1163\times W^{0.75}$	Mcal/d
39	ME_{mg}	dry cow	$0.1163\times W^{0.75}\times1.1$	Mcal/d
40	ME_{p}	9-4 weeks before calving	$((416.2\times exp^{(0.0174/prete)}/35.2\times BW-416.2$ $\times exp^{(0.0174\times prete-63))}/35.2\times BW)/63/0.123)\times0.9/1,000.0$	Mcal/d
41	ME_{p}	3-0 weeks before calving	$((416.2\times exp^{(0.0174\times prete)}/35.2\times BW-416.2$ $\times exp^{(0.0174/prete-63))}/35.2\times BW)/63/0.123)\times1.2/1,000.0$	Mcal/d
42	ME_{l}		$((0.0913\times M_{fat}+0.3678)\times MY)/0.62$	Mcal/d
43	FN	W<66	$2.0\times DMI$	g/d
44	FN	W≥66	$4.8\times DMI$	g/d
45	UN		$0.44\times W^{0.5}$	g/d

* Detailed information on these values and equations are given in JDC (2002) and MAFF (1999).

parity effect. A continuous function was used to describe milk yield (MY) (kg/d) over a full lactation given by Wood (1967). This function had the form of:

$$MY = a\times t_l^{b}\times e^{-ct}$$

where t_l is days of lactation and a, b, and c are parameters. Parameters a, b and c respectively determined the level of yield (intercept), the ascending phase to the peak of lactation, and the descending phase to drying up; they were defined by Hirooka (1992) as follows:

Table 1. Values* for life cycle of dairy cattle and equations* to estimate energy and nutrient requirements quoted from Japanese Feeding Standard for Dairy Cattle (Continued)

Eq.	Variable	Constraint	Equation or value	Unit
46	SP		$0.2\times W^{0.6}$	g/d
47	NP_m		$FN\times6.25+UN\times6.25+SP$	g/d
48	NP_g		$10.0\times DG\times23.5505\times W^{-0.0645}$	g/d
49	EP	$45\leq W<66$	0.75	
50	EP	$66\leq W<120$	0.63	
51	EP	$W\geq120$	0.51	
52	CP_{mg}	before 1st calving	$(NP_m+NP_g)/EP$	g/d
53	CP_{mg}	after 1st calving	$2.71\times W^{0.75}/0.60$	g/d
54	PP		$(1.486\times10.0^{-4}\times prete^3-4.247\times10.0^{-2}\times prete^2-3.173\times prete-0.328)$ $\times(-0.323\times10.0^{-6}\times prete^3+3.000\times10.0^{-4}\times prete^2-9.430\times10.0^{-2}$ $\times prete+11.263)\times6.25-(1.486\times10.0^{-4}\times(prete-63)^3-4.247\times10.0^{-2}$ $\times(prete-63)^2+3.173\times(prete-63)-0.328\times(-0.323\times10.0^{-6}$ $\times(prete-63)^3+3.000\times10.0^{-4}\times(prete-63)^2-9.430\times10.0^{-2}$ $\times(prete-63)+11.263)\times6.25$	g
55	$DCPR$	9-4 weeks before calving	$(PP\times BW/38.5/63)\times0.9/0.6+(4.8\times5.13/2.28)\times6.25$	g/d
56	$DCPR$	3-0 weeks before calving	$(PP\times BW/38.5/63)\times1.2/0.6+(4.8\times6.85/2.42)\times6.25$	g/d
57	NP_f	9-0 weeks before calving	$((1.486\times10.0^{-4}\times Tp^3-4.247\times10.0^{-2}\times Tp^2-3.173\times Tp-0.328)$ $\times(3\times(-0.323)\times10.0^{-6}\times Tp^2+2\times3.000\times10.0^{-4}\times Tp-9.430\times10.0^{-2})$ $+(3\times1.486\times10.0^{-4}\times Tp^2-2\times4.247\times10.0^{-2}\times Tp-3.173)\times$ $(-0.323\times10.0^{-6}\times Tp^3+3.000\times10.0^{-4}\times Tp^2-9.430\times10.0^{-2}$ $\times Tp+11.263))\times6.25$	g/d
58	CP_p		$DCPR/0.60$	g/d
59	NP_{milk}		$1{,}000\times MY\times(1.9+0.4\times M_{fat})/100.0$	g/d
60	CP_l		$(26.6+5.3\times M_{fat})\times MY/0.65$	g/d
61	N_{out}		$(CPi-NP_g-NP_f-NP_{milk})/6.25$	g/d
62	P_{mg}	$W<90$	$0.0156\times W+10.7\times DG$	g/d
63	P_{mg}	$90\leq W<250$	$0.884+0.0500\times W+4.86\times DG$	g/d
64	P_{mg}	$250\leq W<400$	$7.2+0.0215\times W+6.02\times DG$	g/d
65	P_{mg}	before 1st calving	$13.5+0.00207\times W+8.29+DG$	g/d
66	P_{mg}	after 1st calving	$0.0143\times W/0.5$	g/d
67	P_g		$DG\times(1.2+(4.635\times MW^{0.22})\times W^{-0.22})$	g/d
68	P_f	9-4 weeks before calving	$(0.0047\times1.23\times W)\times0.9$	g/d
69	P_f	3-0 weeks before calving	$(0.0047\times1.23\times W)\times1.2$	g/d
70	P_p		$P_f/0.5$	g/d
71	P_{milk}		$0.90\times FCM$	g/d
72	P_l		$P_m/0.5$	g/d
73	P_{out}		$Pi-P_g-P_f-P_{milk}$	g/d
74	Ca_{mg}	$W<90$	$0.0213\times W+20.9\times DG$	g/d
75	Ca_{mg}	$90\leq W<250$	$8.00+0.0367\times W+8.48DG$	g/d
76	Ca_{mg}	$250\leq W<400$	$13.4+0.0184\times W+7.17\times DG$	g/d
77	Ca_{mg}	before 1st calving	$25.4+0.00092\times W+3.61\times DG$	g/d
78	Ca_{mg}	after 1st calving	$0.0154\times W/0.38$	g/d
79	Ca_p	9-4 weeks before calving	$(0.0078\times1.23\times W/0.38)\times0.9$	g/d
80	Ca_p	3-0 weeks before calving	$(0.0078\times1.23\times W/0.38)\times1.2$	g/d
81	Ca_l		$(1.20\times FCM)/0.38$	g/d
82	VA_{mg}		$0.0424\times W$	1,000 IU/d
83	VA_p		$0.0336\times W\times0.9$	1,000 IU/d
84	VA_l		$1.2\times MY$	1,000 IU/d

* Detailed information on these values and equations are given in JDC (2002) and MAFF (1999).

$$a = TMY \div \sum_{l=1}^{lacte} (t_l^b \times e^{-ct_l})$$

$b = 0.208$
$c = 0.0342$

where *lacte* is lactation period and *TMY* is the total milk

Table 2. Equations of constraints for constructing optimal ration model

Constraint	
Dry matter intake (DMI)	$\Sigma a_{ij}x_j \leq DMI_{mg}+DMI_p+DMI_l$
Metabolizable energy requirement (ME)	$\Sigma a_{ij}x_j = ME_{mg}+ME_p+ME_l$
Crude protein requirement (CP)	$\Sigma a_{ij}x_j \geq CP_{mg}+CP_p+CP_l$
Calcium requirement (Ca)	$\Sigma a_{ij}x_j \geq Ca_{mg}+Ca_p+Ca_l$
Phosphate requirement (P)	$\Sigma a_{ij}x_j \geq P_{mg}+P_p+P_l$
Vitamin A requirement (VA)	$\Sigma a_{ij}x_j \geq VA_{mg}+VA_p+VA_l$

yield at the fifth parity. Total milk yields at different parities were calculated by multiplying coefficients reported by Groen (1988).

It was assumed that a heifer is first inseminated at 18 month after birth, that the lengths of pregnancy and lactation are 280 d and 359 d, respectively, and that the calving interval is 14.1 mo (JDC, 2002).

A cow's daily ME requirement ($ME_{(t)}$) was expressed as:

$$ME = ME_{mg}+ME_p+ME_l \qquad \text{(Mcal/day)}$$

where ME_{mg} is the metabolizable energy requirement for maintenance and growth, and ME_p and ME_l are the metabolizable energy requirements for pregnancy and lactation, respectively. The ME requirement for pregnancy (ME_p) was calculated as that at 63 days before calving (MAFF, 1999). The daily DMI, CP, Ca, P and VA requirements were calculated same as the case of ME using these growth and lactation curves as well as the equations (MAFF, 1999) (Table 1). The model simulates daily nutrient requirements on one day time step basis.

Furthermore, excretions for nitrogen (N) and phosphorus (P) were calculated in this model. The daily amount of N in excretions ($N_{out(t)}$) was calculated from the following equation (Table 1):

$$N_{out} = (CP_i\text{-}NP_g\text{-}NP_f\text{-}NP_{milk})/6.25$$

where CP_i is CP intake calculated from the optimum diet optimization model (see the next section), NP_g is the amount of protein retained in the body shown in Table 1 (Eq(48)), NP_f is the amount of protein retained in fetus during pregnancy (Eq(57) in Table 1) and NP_{milk} is the amount of protein in milk during lactation (Eq(59) in Table 1).

The daily amount of P in excretions ($P_{out(t)}$) was calculated from the following equation (Table 1):

$$P_{out(t)} = P_{i(t)}\text{-}P_{g(t)}\text{-}P_{f(t)}\text{-}P_{milk(t)}$$

where $Pi(t)$ is P intake calculated from the optimum diet optimization model (see the next section), $P_{g(t)}$ is the amount of P retained in the body (Eq(67) in Table 1), $P_{f(t)}$ is the amount of P retained in fetus during pregnancy (Eqs(68) and (69) in Table 1) and $P_{milk(t)}$ is the amount of P in milk during lactation (Eq(71) in Table 1). The model simulates daily excretions on one day time step basis.

Optimum diet formulation model

Diet compositions for a post-weaning animal were modeled using linear programming (LP) that simultaneously solved nutrient constraint equations and minimized cost of ration. The model can be stated algebraically as follows:

Minimize $\{Z_{diet} = c_{diet}'x_{diet}\}$
Subject to $A_{diet}x_{diet} \leq, =,$ or $\geq b_{diet}$ and $x_{diet} \geq 0$

where Z_{diet} is the lowest cost of rations, x_{diet} is the vector of activities, c_{diet} is the vector of costs per unit of activity, A_{diet} is the matrix of technical coefficients, and b_{diet} is the vector of right-hand side values.

The six variables (DMI, ME, CP, Ca, P, and VA) obtained from the nutrient requirement model were used as constraints in this model. The equality and inequality of the constraint, as determined by the nutrient of interest for constructing an optimal ration model, are shown in Table 2. ME intake was set equal to the ME requirement and intake CP, Ca, P, and VA were set to exceed the CP, Ca, P and VA requirements, respectively.

In this model, it was assumed that the prices of home-grown feed were zero, while the prices of purchased feed were set by users. This assumption automatically led to the promotion of the use of home-grown feed instead of purchased feed at daily basis. This assumption reflects the government pollicy on livestock production in Japan, because a decline in the domestic feed supply for livestock has resulted in lower self-sufficiency rate of livestock production and thus Japanese government encourages production and utilization of home-grown feed.

The model assumed that a pre-weaning calf was fed whole milk (4.5 kg) when it weighed less than 45 kg followed by both whole milk (4.5 kg) and dietary feed until it weighed 66 kg (MAFF, 1999). It was assumed that the whole milk would be completely consumed and that dietary feed would compensate for deficiencies against energy requirements. When whole milk supplies exceeded a calf's ME requirements, dietary feed ME was zero.

The feeding cost for the pre-weaning calf in these periods was not solved using LP. Instead it was given by:

when $W<45$ kg

$$Z_{diet} = 4.5\times PRI_{milk}$$

when 45 kg$\leq W<$66 kg

Table 3. Culling rate* ($p_{(i)}$) (%) and simulated herd composition (%)

Reproductive cycle	Culling rate		Herd composition	
	Hokkaido	Honshu	Hokkaido	Honshu
0	-	-	25	27
1	17	19	25	27
2	29	33	20	22
3	31	39	14	15
4	39	46	10	9
5	43	47	6	-
6	52	53	-	-
7	55	53	-	-
8	56	71	-	-

* Detailed information is reported in LIAJ (2005).

$$Z_{diet} = 4.5 \times PRI_{milk} + \frac{(MEi_{(i)} - 4.5 \times 0.58)}{3.15} \times PRI_{creep}$$

where PRI_{milk} and PRI_{creep} are the prices of whole milk (yen/kg) and creep feed (yen/kg), respectively, and 0.58 and 3.15 are the metabolizable energy contents of whole milk (11.4% dry matter) and creep feed (88% dry matter), respectively (MAFF, 1999).

Herd dynamics model

This model was constructed based on Hirooka et al. (1998). It was assumed that the herd size was stable, all replacement heifers were home grown, heifers were culled when they failed to conceive, and cows that failed to conceive were culled at the end of lactation.

In the model, the growing period (cycle 0, T_0) was defined as the interval from birth to the first conception. The growing period of heifers was included in this cycle, because all dairy male calves were sold soon after birth in Japan. The first reproductive cycle (cycle 1, T_1) was defined as the interval from the first conception to the end of the first lactation period. For the later reproductive cycle (cycles *2* to *n*), the length of each reproductive cycle (T_2-T_n) was the period from one lactation end to the next lactation end. All cows in the final cycle (T_n) were culled at the end of the *n*th lactation period.

The composition of a cow population was determined by the culling rate ($p_{(i)}$) of the females (the second and third columns in Table 3). It was assumed that heifers and cows that failed to conceive were culled with the ($p_{(i)}$) in each reproductive cycle (T_i).

For a population with N cows (i.e., herd size is N), the number of females in each reproductive cycle is shown in Table 4, and the herd size N is represented as

$$N = N_{(0)} + N_{(1)} + \cdots + N_{(n)} = \sum_{i=0}^{n} N_{(i)}$$

where $N_{(0)}$ and $N_{(i)}$ are the number of females in the growing period and *i*th reproductive cycle, respectively. Provided that the sex ratio is set as 1:1 and the calf survival rate is set as s, the number of surviving male and female calves produced from cows in the *i*th reproductive cycle ($N_{M(i)}$ and $N_{F(i)}$) is calculated as

$$N_{F(i)} = N_{M(i)} = 0.5sN_{(i)}$$

When the number of newborn females of N_0 is used as replacement heifers to maintain a stable herd size, the replacement rate (*r*) can be obtained as

$$N_o = r\sum_{i=1}^{n} N_{F(i)}$$

$$r = N_0 / \sum_{i=1}^{n} N_{F(i)}$$

Therefore, the number of newborn females for sale (N_{SF}) is

$$N_{SF} = (1-r)\sum_{i=1}^{n} N_{F(i)}$$

Note that the number of newborn males for sale (N_{SM}) is

$$N_{SM} = \sum_{i=1}^{n} N_{M(i)}$$

The number of animals in each reproductive cycle was adjusted by the length of the cycle as shown in the next section (see calculation of *Aveday*).

Table 4. Definition of the number of female cattle in each cycle

Cycle	Period (T_i)	Number of females ($N_{(i)}$)	Expression
0	Birth - 1st conception	$N_{(0)}$	N_0
1	1st conception - 1st lactation end	$N_{(1)}$	$N_0(1-p_{(0)})$
2	1st lactation end - 2nd lactation end	$N_{(2)}$	$N_0(1-p_{(0)})(1-p_{(1)})$
3	2nd lactation end - 3rd lactation end	$N_{(3)}$	$N_0(1-p_{(0)})(1-p_{(1)})(1-p_{(2)})$
:	:	:	:
n-1	n-2th lactation end - n-1th lactation end	$N_{(n-1)}$	$N_0(1-p_{(0)})(1-p_{(1)})(1-p_{(2)}) - (1-p_{(n-2)})$
n	n-1th lactation end - nth lactation end	$N_{(n)}$	$N_0(1-p_{(0)})(1-p_{(1)})(1-p_{(2)}) - (1-p_{(n-2)})(1-p_{(n-1)})$

Table 5. Structure of whole-farm LP-model

Constraint	Activities						Right-hand side
	Animal production	Home-grown feed production	Purchase of fertilizer	Working hours	Surplus N	Surplus P	
Land requirements		1					≤Available hectares
Housing requirements	1						≤Available cow place
Labor requirements	a_{ij}^{a}	a_{ij}^{a}		-1			= 0
Feeding requirements	a_{ij}^{a}	$-a_{ij}^{a}$					≤0
Fertilizing requirements (Nitrogen)	a_{ij}^{a}	$-a_{ij}^{a}$	a_{ij}^{a}				≥0
Fertilizing requirements (Phosphorus)	a_{ij}^{a}	$-a_{ij}^{a}$	a_{ij}^{a}				≥0
Farm-level nutrient balance (Nitrogen)	a_{ij}^{a}		a_{ij}^{a}		-1		= 0
Farm-level nutrient balance (Phosphate)	a_{ij}^{a}		a_{ij}^{a}			-1	= 0
Financial coefficients	Gross margin	Cost per ha	Cost per ha	Cost per ha	Cost per unit	Cost per unit	

* a_{ij} is the technical coefficient that relates activity i to constraint j.

Whole-farm optimization model

The model was constructed based on the form of a standard linear programming model as follows:

$$\text{Minimize } \{Z_{\text{farm}} = \mathbf{c}_{\text{farm}}'\mathbf{x}_{\text{farm}}\}$$

$$\text{Subject to } \mathbf{A}_{\text{farm}}\mathbf{x}_{\text{farm}} \leq, =, \text{ or } \geq \mathbf{b}_{\text{farm}} \text{ and } \mathbf{x}_{\text{farm}} \geq 0$$

where Z_{farm} is maximum return of the whole farm, $\mathbf{x}_{\text{farm}}$ is the vector of activities and environmental variables, $\mathbf{c}_{\text{farm}}$ is the vector of gross margins or costs per unit of activity, $\mathbf{A}_{\text{farm}}$ is the matrix of technical and environmental coefficients and $\mathbf{b}_{\text{farm}}$ is a vector of technical-environmental right-hand-side (RHS) coefficients. The activities ($\mathbf{x}_{\text{farm}}$) are given at the top row in Table 5. The activities include: animal production from dairy cows, heifers, and sale calves; feed production for on-farm use with forage crops available for hay and silage making; purchase and application of different kinds of fertilizer; labor force (working hours); and farm level environmental loads (N and P surpluses). The rows of the matrix (Table 5) represent the type and number of constraints used: land requirements, housing requirement, labor requirement, feeding requirements matching home-grown feed with the sums of animal requirements, fertilizer requirements matching nutrient requirements for crop lands with the available nutrients from manure and purchased chemical fertilizer, and nutrient balances determining the surplus of N and P for calculating their levies. The last row is the objective function of the LP model that is to be maximized. In the objective function, production costs and incomes per unit of activity were summed up, and thereby whole farm outputs were calculated on a yearly basis.

Technical coefficients concerning animal production were calculated on a life-cycle basis, whereas all activities except animal production were obtained on a yearly basis in the model. It was therefore necessary to convert yearly basis technical coefficients from the life-cycle basis. For example, a cow's yearly total intake of roughage j (kg/year/animal) was calculated as follows:

$$a_{ij} = (TI_j/\text{Aveday})\times 365$$

where TI_j is the total intake of roughage j of the cow's life cycle, and Aveday is the average period (interval) in each life cycle (day) in a population. TI_j was calculated by summing the daily intake of roughage j in each period of the reproductive cycle ($INTj_{(i)}$) multiplied by the age distribution ($N_{(i)}$) as:

$$TIj = \sum_{i=0}^{n}(N_{(i)} \times INTj_{(i)})$$

and *Aveday* was obtained as follows:

$$Aveday = \sum_{i=0}^{n}(N_{(i)} \times Ti)$$

where $N_{(i)}$ and T_i are the age distribution of cows and the period of each reproductive cycle, respectively. All the feeding requirements (home-grown and purchased feed), all the animal products (milk and culled animal) and farm-level nutrient excretions for N (TN_{out}) and P (TP_{out}) of the animals were re-calculated by converting from a life-cycle basis to a yearly basis in the same way.

In this model, it was assumed that all excretions (feces and urine) by animals were used to produce manure and were applied to home-grown crop land as organic fertilizer.

Table 6. Equations* to estimate nitrogen and phosphorus contents in animal production

Equation	Variable	Constraint	Equation and value	Unit
1	No_1	-	$YBMY\times M_{pro}/6.38$	kg
2	Po_1	-	$YBMY\times M_P$	g
3	No_2	-	$EBP/6.25$	kg
4	Po_2	$W<56$ kg	$7.23W+21$	g
5	Po_2	56 kg$<W<$100 kg	$6.06W+8$	g
6	Po_2	$W>100$ kg	$10.6W-0.00663W^2-399$	g

No_1 is the amount of N in the yearly basis milk yield; Po_1 is the amount of P in the yearly basis milk yield; No_2 is the amount of N in cattle body; Po_2 is the amount of P in cattle body.

YBMY is the yearly basis milk yield; M_{pro} and M_P are protein and P contents in milk; 6.38 is the nitrogen-protein conversion coefficient.

EBP = Empty body protein; EBW = Empty body weight; SBW = Shrunk body weight; W = Body weight (W).

$EBP = 0.2358EBW-0.00013EBW^2-2.418$; $EBW = 0.891SBW$; $SBW = 0.94W$

* These equations are given in ARC (1980) and NRC (2001).

Since the manure N and P applied to crop land are less effective than chemical fertilizer because of their lower fertilizer-N and P equivalency, the amounts of effective N and P in manure (ETN, ETP) were derived using the efficiency index of manure (E_N and E_P, %) against chemical fertilizer and the emission rate of N as ammonia (N_{loss}) as:

$$ETN = TN_{out}\times(1-N_{loss})\times E_N/100$$

$$ETP = TP_{out}\times E_P/100$$

The present model assumed that the fertilizer requirements of home-grown crops varied from the crop yields and their CP contents. Considering the amount of crop uptake from soil, the fertilizer N and P requirements of home-grown crops were obtained as:

$$N_{req} = BN_{req}+(DMY-BDMY)\times CP/6.25$$

$$P_{req} = BP_{req}+(DMY-BDMY)\times P$$

where N_{req} and P_{req} are the N and P requirement (kg/ha), BN_{req} and BP_{req} are the N and P requirements for the annual reference dry matter yield (kg/ha) as basis, DMY is the dry matter yield (kgDM/ha), $BDMY$ is the annual reference dry matter yield as basis, and CP and P are CP and P contents in feed (kg/kgDM) produced from harvested home-grown crop.

From an environmental standpoint, farm-gate balances for N and P were used as indicators of potential N and P losses. N surplus (N_{surp}) and P surplus (P_{surp}) were defined as the N and P differences between exported animal products (milk, calves, and culled cows) from the farm and purchased feed and chemical fertilizer from outside. When the amount of manure applied was less than the fertilizer requirements, the deficiencies were assumed to be met by purchased chemical fertilizer. Equations to estimate N and P contents in animal products are given in Table 6.

In this model, gross margin or cost per unit of activity were given by assuming economic situations in the targeted area. The returns per cattle were calculated with the returns of milk and culled animal minus the costs of purchased feeds, because the costs of home-grown feed are taken into account as separate activities. Milk price in Japan was calculated as:

$$M_{pri} = 73.0+(M_{fat}-3.5)\times 4.0$$

where M_{pri} is milk price (yen) per kg and M_{fat} is milk fat content.

RESULTS

Model evaluation

Since a model is based on empirical equations consisting of many experimental results and assumptions, it in itself is just an assumption unless it can prove a generality. Thus, model evaluation is a very important process in modeling studies.

In this study, two situations of typical dairy production systems with crop production in Japan were simulated to validate the whole-farm model. Production systems in both situations were under full confinement operation (i.e., no grazing). A summary of nutrient and mineral contents and the price of each feed used in this simulation are shown in Table 7. These feed ingredients were those typically available to dairy producers in Japan. The information on ingredients and market prices was obtained from the literature (NARO, 2001; MAFF, 2005a). For pre-weaning calves, the prices of whole milk and creep feed were set 82.44 yen/kg and 70.0 yen/kg, respectively (MAFF, 2005a).

Table 8 shows related input variables of the two situations for dairy and crop mixed farming systems in Hokkaido and Honshu areas. The input variables were taken from the management practice guideline (MAFF, 2005b). The values were from data on the top one-third dairy management practices in Hokkaido (Hokkaido situation) and Honshu areas (Honshu situation). According to the guideline, it was assumed that utilization of home-grown feed and purchased roughage for cows was limited to less

Table 7. Dry matter (DM), metabolizable energy (ME), crude protein (CP), calcium (Ca), phosphorus (P), and vitamin A (VA) contained in each feed applied to the structuring of optimal ration

Ingredient	Purchased feed							Home-grown feed		
	Corn	Barley	Bran	Beet pulp	Soybean cake	Mineral block	Alfalfa hay cube	Timothy silage	Alfalfa silage	Maize silage
DM (kg/kg)	0.87	0.88	0.87	0.87	0.88	0.10	0.89	0.3	0.24	0.26
ME (Mcal/kg)	3.09	2.84	2.41	2.44	2.95	0.00	1.79	0.73	0.49	0.64
CP (g/kg)	80	106	157	109	461	0	147	46	39	21
Ca (g/kg)	0.26	0.62	1.13	5.11	2.91	22.00	11.86	1.47	4.04	0.74
P (g/kg)	2.68	3.35	9.57	0.78	6.18	10.00	2.58	0.9	0.65	0.71
VA (1,000 IU/kg)	0.00	0.00	0.00	0.00	0.00	0.00	11.60	4.80	3.87	4.43
Prices (yen/kg)	39.18	44.74	32.17	49.58	68.90	42.50	51.04	0.00	0.00	0.00

than 45% and 5% of the ME requirements, respectively (Table 8). In addition, the chemical fertilizer requirements of home-grown feed (BN_{req}, BP_{req}) were assumed to be 70 kg N/ha and 31 kg P/ha for pasture and 190 kg N/ha and 87 kg P/ha for maize (JLIA, 1990). The N emission of manure as ammonia was set 25%. The fertilizer equivalency of manure for N and P were assumed to be 30% and 60%, respectively (MAFF and NARO, 2004). The price of purchased chemical fertilizer (0.15 kg N/kg, 0.15 kg P/kg) was 95.34 yen/kg and the labor cost was assumed to be 1,612 yen/hour (MAFF, 2005b). Other fixed costs, such as fixed assets of the farm and the costs of land, barns and machinery, were obtained from statistics (MAFF, 2005c).

The fixed milk prices were set in Hokkaido and Honshu, respectively. The prices of male and female calves were both set as 38,458 yen/animal and that of culled cows was set as 1,508 yen per 10 kg body weight (MAFF, 2005a). The annual yield of maize and pasture (timothy and alfalfa) were assumed to be 13,770 kg DM/ha and 5,740 kg DM/ha in Hokkaido and 12,393 kg DM/ha and 6,020 kg DM/ha in Honshu (JLIA, 1990).

Figure 2 and 3 illustrate the predicted daily ME intake and DM intakes of home-grown feed by maintenance and growth, pregnancy and lactation stages for a cow in Hokkaiso. The results show increased ME intake and dry matter intake of home-grown feed during late pregnancy and lactation stages. Distributions of females in each reproductive cycle are shown in the 4th and 5th columns in Table 3 for Hokkaido and Honshu, respectively.

Comparisons between values in the management practice guideline for the two situations and predictions from the present model are given in Table 9. There was small discrepancy in the number of cows and production costs except labor cost in both Hokkaido and Honshu situations. In contrast, large differences of labor costs were found for both situations. This result may reflect the

Table 8. Input variables for two situations (Hokkaido and Honshu areas)

Items	Situation	
	Hokkaido	Honshu
Maximum allowance of culling (parity)	5	4
Milk yield (kg/cow/year)	8,600	8,400
Milk price (yen/kg)	73.6	89.1
Labor requirement for feeding (hour/cow)	66	104
Available hectares (ha)		
Pasture	51.1	12.9
Maize	12.8	5.5
Labor requirement for home-grown feed (hour/ha)		
Pasture	21.2	42
Maize	35.2	51.5
Yield of home-grown feed (kg DM/ha)		
Pasture	5,740	6,020
Maize	13,770	12,393
Home-grown feed production cost[a] (yen/ha)		
Pasture		
Timothy	77,715	77,715
Alfalfa	55,577	55,577
Maize	161,670	151,775
Utilization of purchased roughage (Alfalfa hay cube)	-	5% of MEicow
Restriction for home-grown feed utilization	-	≤45% of MEicow
Fixed cost (yen/cow)	164,093	157,956

Home-grown feed production cost is calculated as feed production cost minus fertilizer cost, labor cost, fixed cost, and land cost MAFF (2005c).

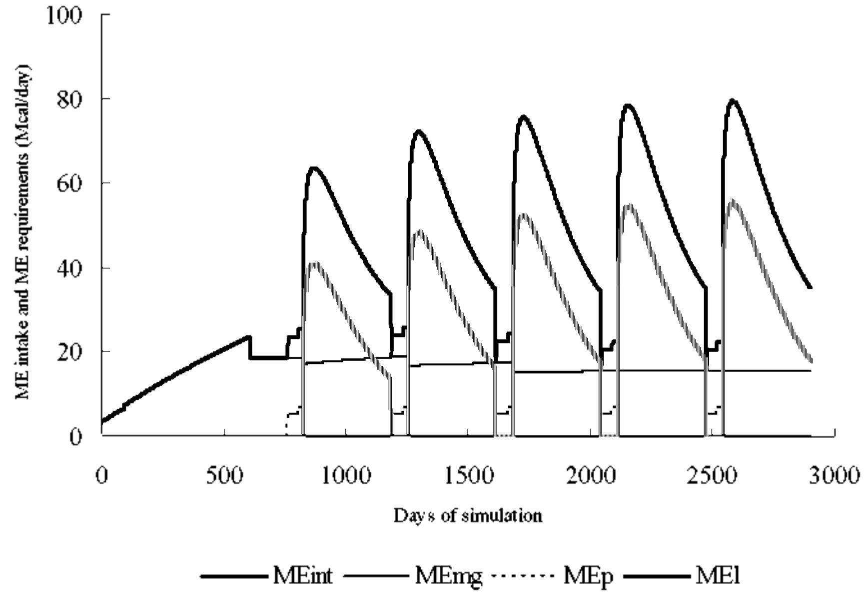

Figure 2. Metabolizable energy intake (ME_{int}) and metabolizable energy requirement for growth and maintenance (ME_{mg}), pregnancy (ME_p) and lactation (ME_l) of a cow in her life cycle (Hokkaido).

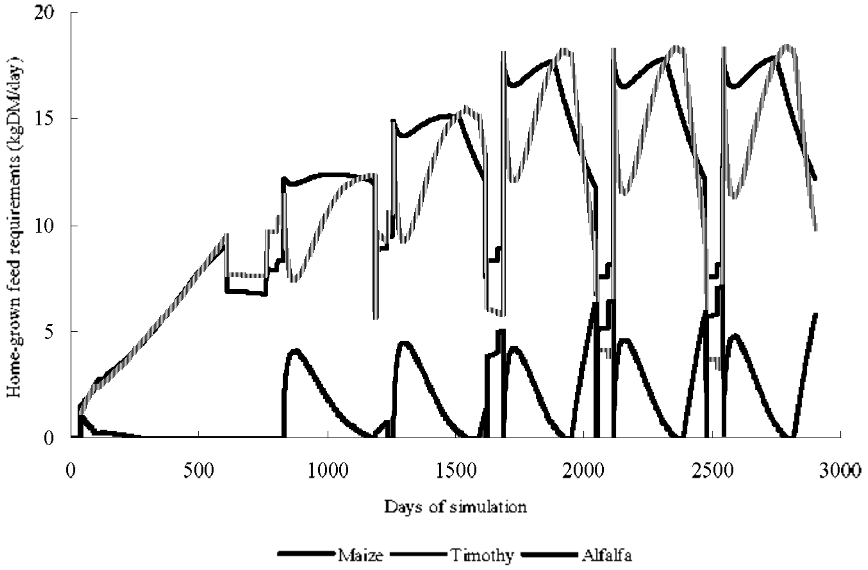

Figure 3. Dry matter intake of home-grown feed of a cow in her life cycle (Hokkaido situation).

Table 9. Comparison between management guidelines and predictions from farm-LP model

Items	Hokkaido		Honshu	
	Management guideline	Model predictions	Management guideline	Model predictions
Number of cow	80	89	40	43
Labor requirement (hour)	6,800	7,480	5,640	5,378
Labor cost (yen)	13,500,000	8,833,857	8,300,000	5,444,842
Feed cost (yen)	17,200,000	17,599,729	10,500,000	9,653,892
Revenue (yen)	52,500,000	51,558,670	31,000,000	28,921,160
Total cost (yen)	45,000,000	41,217,320	25,000,000	22,013,330
Net profit (yen)	7,500,000	10,341,350	6,000,000	6,907,830
N surplus (kg/ha)	-	76	-	159
P surplus (kg/ha)	-	65	-	87

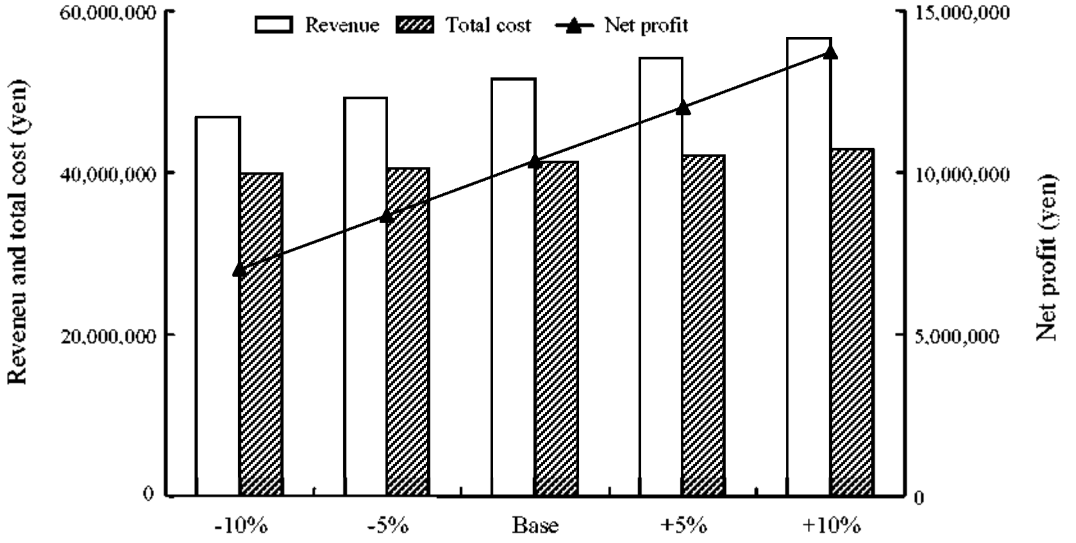

Figure 4. Economic impacts in change of milk yield (Hokkaido situation).

difference in the calculation way of labor cost: the management practice guidelines assume that full-time employees with higher payment would be hired, whereas the present model calculates labor cost by summing the labor cost per hour taken from standard management practices in statistics. Without the difference in labor costs, the model predictions for revenues, total costs and net profits in both Hokkaido and Honshu agreed well with the values given in the management practice guideline. This result indicated that the present model would be applicable to actual situations for dairy and crop mixed farming systems in Japan.

N surplus was higher in Honshu than in Hokkaido. This may be mainly because of the difference of production intensities in the situations; the animal intensity in Honshu is more than that in Hokkaido. The animal intensity difference between the two areas is reported in Tsuiki and Harada (1996). Considerably higher P surplus was obtained in the situations. The unexpected result may be reflected from utilization of fixed chemical fertilizer with higher P content (0.15 kg N/kg, 0.15 kg P/kg). P control by the chemical fertilizer would make it possible to reduce the P surplus.

Sensitivity analysis

Sensitivity analyses allow us to examine the impacts of changing values of susceptible variables of the integrated system on economic variables (revenue, total cost, and net profit) as well as environmental variables (N and P surpluses). In this study, changes of ±5% and ±10% with respect to the assumed value of milk yield (MY) were examined in Hokkaido. In this section, only sensitivity results for Hokkaido situation were shown, because the similar results were obtained for Honshu situation.

Figure 4 and 5 show the effects of milk yield on economic (revenue, total cost, net profit) and environmental

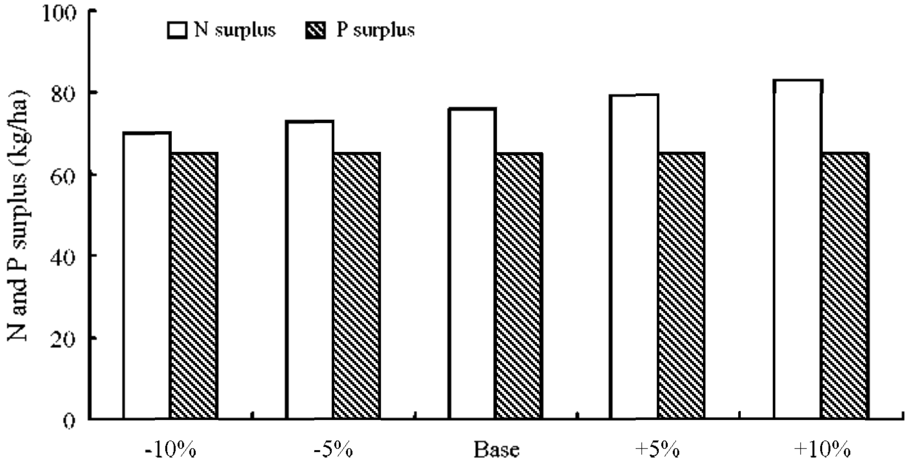

Figure 5. Environmental impacts in change of milk yield (Hokkaido situation).

variables (N and P surpluses), respectively. Changes in MY were made at a time while all other variables were kept constant.

The results in Figure 4 showed that each of these economic variables was sensitive to changes in MY. The high sensitivities of revenue and total cost were obtained, since milk sales provided the highest income in the situation. An increase in MY led to a rise in the revenue due to a rise in milk sales. To fulfill the higher nutritional requirements of the animal caused by higher milk production, the model compensated for the quality and quantity of the diet by increasing the amounts of purchased feed, which increased total cost. The increment in revenue was higher than that in total cost, providing a positive net profit for the farm. Economically, these results indicated that farmers should raise higher-performance cows in this situation.

N and P surplus were slightly sensitive to changes in MY (Figure 5). Increasing MY caused rises in both the input and output of N and P. These were expected because more purchased feed was utilized and more milk was sold. However, the higher nutrient inputs from the purchased feed led to increased amount of excretions for use as manure. Consequently more organic fertilizer (manure) was utilized to complement the chemical fertilizer. That is, a rise in the purchased feed requirement reduced the chemical fertilizer requirement when the total fertilizer requirement was constant. P surplus was less sensitive than N surplus. The low sensitivity of P may be resulted from excess P fertilization by the utilization of purchased chemical fertilizer with high P content (0.15 kg N/kg, 0.15 kg P/kg). Environmentally, these results indicated that the nitrogen load on the environment was substantially increased by improving MY of cows in this situation.

DISCUSSION

The objective of this study was to develop a bio-economic simulation model for Japanese dairy production systems with forage crop production. The present model includes not only bio-economic factors but also environmental factors, and thus provides a useful tool for evaluating and comparing the environmental impacts as well as the economic performance of alternative systems. For animal and crop producers, it is important to quantify the trade-off between profitability and environmental loads derived from production and to evaluate the effects of recycling nutrients on the profitability of the whole farm. Janssen and Van Ittersum (2007) reviewed studies using bio-economic farm models and pointed out that such models may permit us to consider many activities, restrictions, and new production techniques simultaneously while also allowing us to examine the effects of changing parameters through sensitivity analysis. Those authors also noted that a bio-economic farm model can be defined as a model that supports farmers' resource management decisions by describing current and alternative production possibilities in terms of required inputs to achieve certain outputs and associated externalities.

In Europe and the USA, bio-economic farm models that include economic and environmental factors have been developed to evaluate dairy and forage crop mixed farming systems at the whole-farm level. These models were used to determine the optimum cropping system for both manure nutrients and crop nutrients (Henry et al., 1995), to evaluate the impacts of institutional, technical and price changes on the farm plan as well as the impacts of nutrient losses on the environment while maximizing farm profitability (Berentsen and Giesen, 1995), and to analyze the effects of environmental policy and management measures on the economic and ecological sustainability of dairy farms (Steverink et al., 1994; Koenen et al., 2000; Berentsen, 2003; Berentsen and Tiessink, 2003; Berntsen et al., 2003; Van Calker et al., 2004). Rotz et al. (1999a) developed a simulation model for dairy and forage crop mixed farming systems that integrates many biological and physical processes on a dairy farm. The model revised by Rotz and Coiner (2006) has been applied to evaluate economic and environmental feasibility of a dairy farm with changing the management (Rotz et al., 1999b; Soder and Rotz, 2001; Rotz et al., 2002; Rotz et al., 2005; Ghebremichael et al., 2007).

In Asian countries, the integration of crop and animal production is well developed and most on ruminant livestock are found on such mixed farming systems (Devendra and Thomas, 2002). Devendra (2007) reviewed improved crop-animal integration systems in Asia and advocated that system approach is required to interpret the contribution of the many components in mixed farming systems that identified through detailed analysis of the need and constraints. In our companion paper (Kikuhara and Hirooka, 2008), the model described here is applied to evaluate integrations systems between forage rice and dairy cattle production in Japan.

The model in the present study was used to find an optimum combination of feed resources that minimize daily feed cost and to predict the effects of alternative management decisions on farm profitability and the environment within the existing framework. The results of sensitivity analyses showed that many variables affect the optimal farming system, indicating the complexity of dairy and crop mixed farming systems. The economic and environmental variables were sensitive to the change in milk yield. Increased milk yield caused total sales and cost, and thereby higher net profit. Further, higher milk yield also raised the amounts of N and P surpluses (Figure 5). These results were in good agreement with those in Rotz et al.

(1999b). These sensitivity analyses allow us to assess how changes in the values of susceptible variables (both economic and environmental variables) affect certain whole-farm outputs.

There are two important characteristics of the present model. The first is applicability. The present model appears to be easily changed to accommodate other dairy and forage crop production circumstances in Japan by changing input variables assumed in the study. This is because the biological relationships and assumptions used in the model are general. In this respect, the model is flexible and can be used to contribute to insights obtained by carrying out proper calculations and publishing the findings for mixed farming systems in wide-ranging production circumstances. The model allows us to modify even the structure (i.e., equations) of the model and to replicate assessments for a vast range of spatial conditions and farm practices. For example, the users may change from the feeding standards for Japanese dairy cattle (MAFF, 1999) to other feeding standards, allowing them to transfer the model between different locations and farms in the USA (NRC, 2001) and the UK (AFRC, 1993) without changing the basic framework of the model. Jansen and Van Ittersum (2007) point out that an easily transferable bio-economic farm model will enable a group of researchers to work jointly by allowing the re-use of results of simulations across farm types and locations.

The second important characteristic is that the model was developed using both of system simulation (Dent and Blackie, 1979) and linear programming which are typically adopted methodologies to construct models for agricultural systems; system simulation is used to predict nutrient requirements and herd dynamics and linear programming is used for diet optimization and whole farm optimization. In general, system simulation consists of modeling the strategies and biological processes of agricultural systems and simulating between these processes. The methodology has been widely used to simulate animal properties in animal science fields (Sanders and Cartwright, 1979ab; Groen, 1988; Hirooka et al., 1998; Rotz et al., 1999a; Rotz and Coiner, 2006). On the other hand, linear programming has been extensively used to investigate livestock production systems at farm level. The methodology offers the potential to identify optimal systems and many models at farm have been constructed using this methodology (Berentsen and Giesen, 1995; Van Calker et al., 2004). In addition, the present model is unique in that the linear programming is utilized twice in the optimum diet formulation model on a daily basis and the whole-farm optimization model on a yearly basis. Despite the uniqueness, it should be noticed that optimization in each sub-model dose not always provide optimal at the whole farm level; in this model, use of home-grown feed is maximized by setting prices of zero in the optimum diet formulation model, but production costs for home-grown feed are only taken account in the whole farm optimization model. The present model put emphasis on encouragement of utilizing home-grown feed in order to enhance self-sufficiency of feed production advocated by Japanese government.

In this study, a normative approach was adopted, because the model's objective was to find optimal solutions and alternatives to the problems for mixed farming systems. As pointed out by Janssen and Van Ittersum (2007), however, there is a gap between normative-derived advice given to a farmer and the farmer's actual situation. To overcome this problem, positive approaches, which try to model the farmer's actual behavior by studying farm responses and trying to understand them, should be adopted and incorporated into the simulation process with the model. However, this kind of argument is beyond the scope of this study.

Finally, no simulation models can demonstrate a real system completely. Consequently, models should be continuously improved by incorporating updated knowledge and information. Perhaps with further improvement through verification and validation of the model, a more refined and sophisticated model can be developed and thereafter updated.

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