A Dairy Herd Model for Use in Whole Farm Simulations

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ABSTRACT

A dairy herd submodel was created for integration with other farm submodels to form DAFOSYM, a dairy farm simulation model. The herd submodel determines the best mix of available feeds to meet the fiber, energy, and protein requirements for each of six animal groups. The groups are early-, mid-, late-, and nonlactating cows, heifers over 1 yr old, and younger heifers. Feed intake, milk production, and manure dry matter and nutrient (N, P, and K) excretions are functions of the nutrient content of the diets. Required feed characteristics include crude protein, rumen degradable protein, acid detergent insoluble protein, net energy of lactation, neutral detergent fiber, total digestible nutrients, P, and K concentrations. Feed intake is predicted with fill and roughage units. These units are functions of feed neutral detergent fiber adjusted for particle size distribution and the relative rate of ruminal digestibility or physical effectiveness of the fiber. The herd submodel predicted feed intakes, nutrient requirements, diets, and manure excretions similar to those recommended or measured for dairy animals. When integrated with other farm components in DAFOSYM, the comprehensive model provides a useful tool for evaluating the long-term performance and economics of alternative dairy farm systems.
(**Key words:** dairy herd, model, production, system)

Abbreviation key: ADIP = acid detergent insoluble protein, **ASAE** = American Society of Agricultural Engineers, **DAFOSYM** = Dairy Forage System Model, **FU** = fill unit, **RU** = roughage unit.

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INTRODUCTION

The U.S. dairy industry faces complex issues related to improving efficiency, reducing negative impacts on the environment, and developing a more competitive position in the world economy. Many of these issues must be addressed at the local farm level using a systematic whole farm approach. All major farm components, the interactions among components, and their interaction with the environment must be considered, and an interdisciplinary modeling approach is required.

The U.S. Dairy Forage Research Center (Madison, WI) has developed the Dairy Forage System Model (**DAFOSYM**), a simulation model of the dairy farm. Crop growth, harvest, storage, feeding, and animal performance are simulated over many weather years to investigate the whole-farm impact of strategic management decisions. Simulations have been used to evaluate and compare a variety of feed production systems (24, 25). Recent work has added manure production and handling to allow analyses of manure management practices (5). Current interest is in expanding the model to evaluate the effects of various cropping systems and feed supplementation strategies on the environmental impact and profitability of farms (4).

A dairy herd submodel was needed to allocate a variety of farm-grown and purchased forages and concentrates to all animals on the farm and to predict feed intake, animal response, and manure excretion. Comprehensive animal models (3, 29) provided more complexity than was needed for the farm-level management decisions addressed by DAFOSYM. In addition, inherent uncertainties in these types of models reduced their robustness for this application. A model was required that functioned more on the level of ration balancing programs commonly used throughout the dairy industry. Such models normally use a linear program to determine the mixture of available feeds that satisfy nutrient requirements while minimizing feed cost or maximizing profit (33). The NRC (23) has established recommended nutrient requirements that are often used in formulating rations for dairy animals of various breeds, ages, and milk production.

A dairy herd submodel was developed for DAFOSYM that formulated rations based on NRC (23) recommendations with modifications to accommodate variations in intake associated with forage quality. Enhancement over previous versions was required to accommodate a broader range of feeds and feeding practices (4, 25). Specific objectives were: 1) develop a model that predicted feed intake, milk production, and manure excretion with rations balanced to meet fiber, energy, and protein requirements for a herd consisting of six animal groups; 2) evaluate the accuracy of the model by comparing these predictions to other widely accepted models and databases; and 3) evaluate the usefulness of the model when integrated with crop production, feeding, and manure handling submodels in a whole farm simulation.

MATERIALS AND METHODS

The model was developed to predict the performance of a dairy herd consisting of growing heifers, lactating cows, and nonlactating cows. The model was organized in six sections. First, the characteristics of the major animal groups were established. Next, the feed characteristics were set and available feeds were allocated to the animal groups. Each group's requirements for fiber, energy, and protein were determined, and a linear program was used to find the least cost, nutritionally balanced mix of feeds to meet these requirements. Finally, based on the diet fed, the quantity and nutrient content of the manure produced was determined.

Animal and Herd Characteristics

The herd was described as six animal groups: young stock <1 yr old, heifers >1 yr old, three groups of lactating cows, and nonlactating cows. There was flexibility in how the three groups of lactating cows were divided, but generally they represented early-, mid-, and late-lactation cows. All cow groups were further subdivided into primiparous and multiparous cows, and a portion of each were set by the user as the culling rate of the herd. The seven available types were large Holstein, average Holstein, small Holstein, Brown Swiss, Ayrshire, Guernsey, and Jersey.

Five characteristics were used to describe each group: potential milk yield, milk fat content, BW, change in BW, and fiber ingestive capacity. For cows, continuous functions were used to describe each characteristic over a full lactation (Table 1, Figure 1). A modified infinite Gamma function was chosen as the base model for each. This function had shape characteristics typical of animal responses, and it was easily fitted to data by logarithmic transformation and iterative least-squares procedures. This function had the form $Y = A\,(w + s)^{b}\,e^{[-c(w+s)]}$; where: A = the intercept, w = week of lactation, s = shift factor (in weeks), b = exponent of time, and c = the exponential rate of change. Parameters b and c defined the shape of the curve, and parameter A determined the peak.

Parameters were first established for an average Holstein herd producing 9070 kg of milk annually with an average BW of 600 kg during mo 2 through 5 of lactation. Data from the functions of Congleton and Everett (7) were used to generate milk yield curves for primiparous and multiparous animals ranging in production from 4500 to 11,400 kg. Regressions between function parameters and lactational yields were used to derive lactation curve parameters for a herd production of 9070 kg of milk. Milk fat percentage was described by a function from Williams (36), and parameters for the BW functions were derived with data from various sources (9, 12, 19, 20). Data from several studies were used to derive parameters for the NDF ingestive capacity functions (6, 8, 10, 11, 13, 16, 17, 31, 36, 37). Published NDF intakes for cows in late lactation varied greatly; therefore, equation parameters were set to be consistent with energy densities and DMI recommended by NRC (23). The (A) parameters of all functions for the average Holstein herd were then scaled to match typical production characteristics of other animal types (Table 2). The characteristics of replacement heifers varied only with animal type (Table 2).

Although the feeding groups could be modified, the normal procedure was to assume that 16% of the cows were in early lactation, 23% were in mid lactation, 46% were in late lactation, and 15% were nonlactating. Following a standard lactation cycle, this implied that the four groups represented wk 0 to 9, wk 10 to 22, wk 23 to 48, and wk 49 to 56, respectively. The animal characteristic functions were integrated over the appropriate weeks of the lactation cycle for a given group to determine the average characteristic over that period. The change in BW was the average daily change in BW over the period. Each characteristic of the group was then determined as the average of the primiparous and multiparous subgroups weighted by the number of animals in each subgroup. The herd was modeled with a 56-wk lactation cycle, but feed intake and milk production were totaled for the calendar year.

Feed Characteristics

Feed characteristics required to balance rations and predict DMI included CP, RDP, acid detergent insoluble protein (**ADIP**), NE_L, and NDF. The TDN, P, and K concentrations were also used to predict manure excretion. Typical or average parameters for major feeds are listed in Table 3 (23, 33). For forages, feed characteristics vary widely as influenced by by growing, harvest, and storage conditions. In DAFOSYM, functions in the growth, harvest, and storage submodels predict forage CP, RDP, ADIP, and NDF concentrations (24).

To reduce the number of inputs from other components of the farm, forage NE_L (Mcal/kg of DM) and TDN (fraction of DM) contents were predicted from forage NDF (fraction of DM):

For alfalfa:	$NE_L = 2.323 - 2.16$ (NDF)	[1]
For corn silage:	$NE_L = 2.394 - 1.93$ (NDF)	[2]
	$= 2.536 - 2.71$ (DM)	[3]
For small grain silages:	$NE_L = 2.826 - 2.43$ (NDF)	[4]
For grasses:	$NE_L = 2.863 - 2.62$ (NDF)	[5]
For all forages	$TDN = (NE_L + 0.12)/2.45$	[6]

The NE_L of corn silage was the lesser of equations 2 and 3, which limited available NE_L as the crop matured (1, 26). Most functions were obtained from Mertens (15, 17), but the corn DM and small grain functions were derived from published data (1, 23).

Except for silages, the ruminal degradability of each feed was assigned a constant value as listed in Table 3. In all types of silage, protein degradability was determined from NPN (fraction of total N) content (25). All NPN and 50% of the true protein was assumed to be soluble and degraded in the rumen (14). Thus for silage i, the RDP (fraction of CP) was given by:

$$RDP_i = 0.5 + 0.5\ (NPN_i) \qquad [7]$$

Two limitations of the NRC (23) system were revised to create a more flexible ration formulation routine. The first limitation was intake prediction; the NRC system only provided the DMI required for an animal to obtain adequate NE_L. A maximum forage intake implies that ruminal fill is at the maximum that the cow will tolerate and still maintain a target milk production. A theoretical fill unit (**FU**) was defined to represent the filling effects of forages and concentrates based on their NDF concentration, fraction of particles that were large or small, and filling factors for large and small particle NDF. The FU system was similar to the fill-adjusted NDF concept suggested by Mertens (17), but the concept was expanded to differentiate between the filling effects of large and small fiber particles. The FU concentration in each feed was determined by:

$$FU_i = (FFL_i)\ (NDFL_i)\ (LP_i) + (FFS_i)\ (NDFS_i)\ (SP_i) \qquad [8]$$

where FFL_i = fill factor of large particles in feed i, $NDFL_i$ = NDF concentration of large particles in feed i (fraction of DM), LP_i = large particles (e.g. alfalfa stem or corn stover) in feed i (fraction of DM), FFS_i = fill factor of small particles in feed i, $NDFS_i$ = NDF concentration of small particles in feed i (fraction of DM), SP_i = small particles (e.g. alfalfa leaves or corn grain) in feed i (fraction of DM) or $SP_i = 1.0 - LP_i$, and NDF_i = NDF concentration in feed i (fraction of DM). Thus the NDF concentration in each feed is given by:

$$NDF_i = (NDFL_i)\ (LP_i) + (NDFS_i)\ (SP_i) \qquad [9]$$

Large and small particle fractions in forages were related to physical characteristics of the crop. For alfalfa, stems were defined as large, slow-degrading particles that occupy more space in the rumen. The small particles were leaves that rapidly degrade in the rumen and thus have less filling effect. For corn and small grain silages, 85% of the stover was defined to be large particles, and the remainder of the plant was small particles. For grass forages, 70% of the crop was assumed to be large particles; the NDF concentrations in large and small particles were equal. For other forages,

TABLE 1. Functions used to describe dairy cow characteristics through a 56-wk lactation cycle.

Characteristic	Animal type	Function[1]
Milk yield, kg/d	Primiparous cows	$MY_1(w^{0.178})(e^{-0.021\ w})$
	Multiparous cows	$MY_2(w^{0.2218})(e^{-0.034\ w})$
Milk fat, %	Primiparous cows or multiparous cows	$MF(w^{-0.24})(e^{0.016\ w})$
Body weight, kg	Primiparous cows	$BW_1(w + 1.71)^{-0.0730}[e^{0.00869(w + 1.71)}]$
	Multiparous cows	$BW_2(w + 1.57)^{-0.0803}[e^{0.00720(w + 1.71)}]$
Fiber ingestive capacity[2], FU/(kg of BW)/d	Primiparous cows	$FIC_1(w + 0.857)^{0.360}[e^{-0.0186\ (w + 0.857)}]$
	Multiparous cows	$FIC_2(w + 3.000)^{0.588}[e^{-0.0277(w + 3.00)}]$

[1]MY, MF, BW, and FIC are milk yield, milk fat content, BW, and fiber ingestive capacity parameters, respectively (See Table 2). w is week in the lactation cycle, 1 to 56.

[2]FU = Fill units (Table 3).

the proportion of large and small particles and their NDF concentrations varied with growing, harvest, and storage conditions (24). No attempt was made to relate

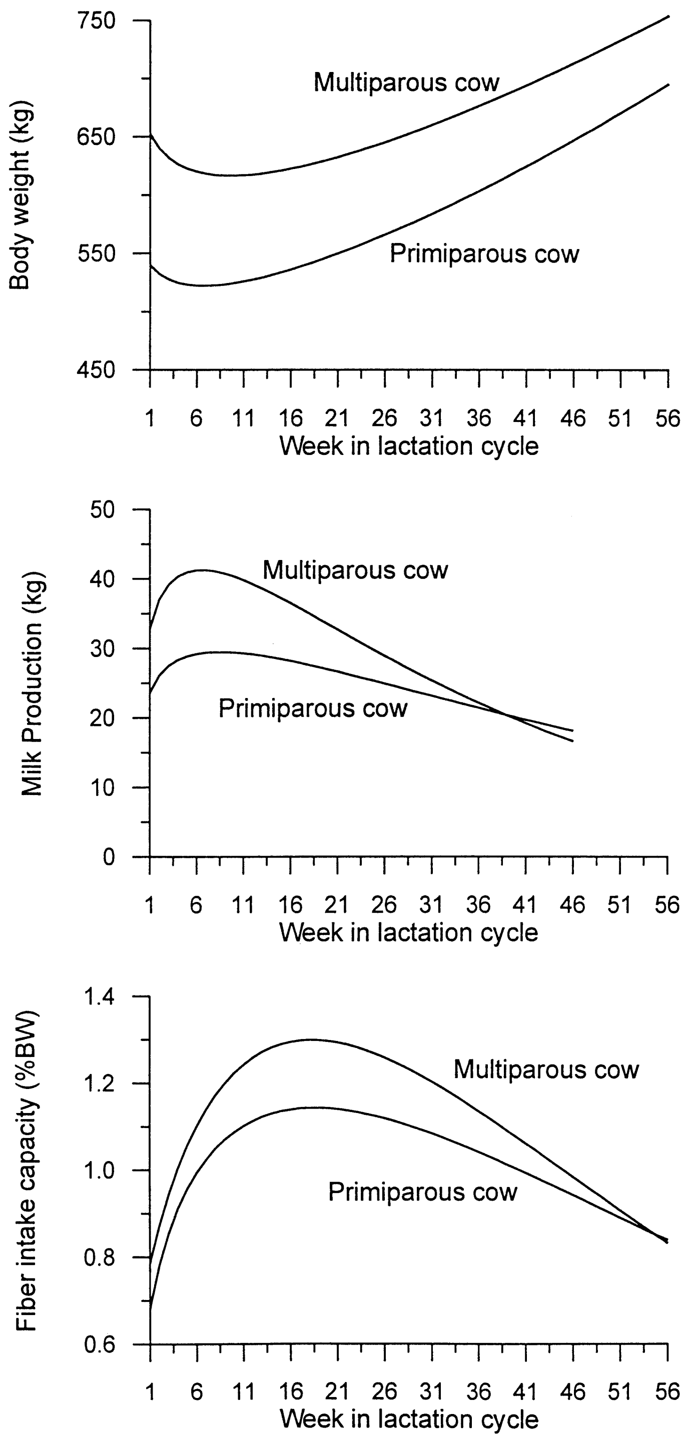

Figure 1. Modeled changes in BW, milk production, and fiber ingestive capacity throughout the lactation cycle of typical Holstein cows. (Equations for each are listed in Table 1).

TABLE 2. Milk yield (MY), milk fat content (MF), BW, and fiber ingestive capacity (FIC) parameters for growing heifers and lactating cows of various breeds. For lactating cows, these parameters must be used with the associated equations of Table 1 to obtain the milk yield, milk fat and fiber ingestive capacity throughout the lactation cycle.[1]

Animal type	MY (kg/d)	MF (%)	BW (kg)	FIC[2] (FU/kg/d)
Large Holstein				
Young heifer	—	—	218	1.050
Older heifer	—	—	517	1.100
Primiparous cow	26.5	5.0	624	0.564
Multiparous cow	37.3	5.0	759	0.388
Average Holstein				
Young heifer	—	—	198	1.050
Older heifer	—	—	470	1.100
Primiparous cow	24.1	5.0	567	0.564
Multiparous cow	34.0	5.0	690	0.388
Small Holstein				
Young heifer	—	—	178	1.050
Older heifer	—	—	423	1.100
Primiparous cow	21.7	5.0	510	0.564
Multiparous cow	30.6	5.0	621	0.388
Brown Swiss				
Young heifer	—	—	184	1.050
Older heifer	—	—	437	1.100
Primiparous cow	22.4	5.7	527	0.564
Multiparous cow	31.6	5.7	642	0.388
Ayrshire				
Young heifer	—	—	166	1.050
Older heifer	—	—	395	1.100
Primiparous cow	20.3	5.9	476	0.564
Multiparous cow	28.5	5.9	580	0.388
Guernsey				
Young heifer	—	—	150	1.050
Older heifer	—	—	357	1.100
Primiparous cow	18.3	6.9	431	0.564
Multiparous cow	25.8	6.9	524	0.388
Jersey				
Young heifer	—	—	139	1.050
Older heifer	—	—	329	1.100
Primiparous cow	20.0	7.5	397	0.666
Multiparous cow	28.0	7.5	483	0.458

[1]For lactating cows, MY, MF, BW, and FIC are parameters for equations listed in Table 1. For heifers, BW is the body weight and FIC is the fiber ingestive capacity.

[2]FU = Fill units (Table 3).

particle size with harvest method or length-of-cut; this will require future refinement.

Fill factors served as weighting factors for increasing or decreasing the effect that the NDF in feed particle size pools had on rumen fill. Values were assigned that were inversely related to the digestibilities of those particles, i.e., a greater value represented a lower fiber digestibility and thus greater fill. Initial values were selected considering the relative fiber digestibilities of feed constituents; 1.0 was the average of all feeds. Large particles were defined to have more than three times the filling effect of small particles in alfalfa and corn silage, with less difference between the particle pools for grass, small grain, and pasture forages. Grain, high-moisture corn without cobs, and protein and fat supple-

TABLE 3. Typical feed characteristics used to balance rations and predict manure excretion (23, 33)[1].

	NDF	FU	RU	TDN	NE_L	CP	RDP	ADIP	P	K
	(% of DM)				(Mcal/kg)	(% of DM)	(% of CP)		(% of DM)	
Forages[2]										
Pasture	53	64.7	49.8	66	1.49	20.0	81	2.0	0.26	2.54
Low quality alfalfa silage	47	53.5	42.8	58	1.31	18.0	78	5.0	0.23	1.71
High quality alfalfa silage	40	44.0	35.8	64	1.46	21.0	78	5.0	0.26	2.54
Low quality alfalfa hay	49	56.2	44.8	56	1.26	17.0	70	8.0	0.23	1.71
High quality alfalfa hay	42	46.7	37.8	63	1.42	20.0	70	5.0	0.25	2.30
Grass silage	50	64.5	47.0	70	1.60	16.0	75	7.5	0.35	2.90
Small grain silage	55	73.4	52.5	43	0.94	13.5	78	5.9	0.38	1.39
Corn silage	47	57.7	44.0	62	1.41	8.4	65	5.9	0.22	1.00
Energy supplements										
Corn grain	10	4.0	0	88	1.96	10.0	48	2.0	0.30	0.36
High moisture corn	10	4.0	0	88	2.04	10.0	60	2.0	0.30	0.36
Barley grain	19	7.6	0	84	1.94	13.5	73	2.0	0.38	0.47
Animal or vegetable fat	0	0.0	0	0	5.84	0.0	0	0	0.00	0.00
CP supplements										
Canola seed meal	36	14.4	0	69	1.72	44.0	70	5.0	1.13	1.40
Corn gluten feed	45	18.0	0	80	1.92	25.0	75	2.0	0.90	0.64
Cottonseed meal	32	12.8	0	78	1.72	44.7	55	3.0	1.18	1.35
Soybean meal, 44% CP	14	5.6	0	84	1.94	49.0	70	3.0	0.68	2.00
Soybean meal, 48% CP	10	4.0	0	87	2.01	55.0	70	3.0	0.70	2.30
Urea	0	0.0	0	0	0.00	281.0	100	0.0	0.00	0.00
RUP and oil seed supplements										
Blood meal	12	4.8	0	66	1.50	87.0	20	10.0	0.26	0.10
Brewers grain, dry	45	18.0	0	66	1.50	25.4	50	10.0	0.55	0.09
Corn gluten meal, 60% CP	10	4.0	0	89	2.07	67.2	45	5.0	0.54	0.21
Cottonseed	44	17.6	0	96	2.23	23.0	60	8.0	0.64	1.00
Distillers grain, dry	43	17.2	0	86	1.98	23.0	50	15.0	0.43	0.18
Feather meal	12	4.8	0	70	1.60	90.0	30	10.0	0.72	0.31
Fish meal	8	3.2	0	73	1.68	66.7	40	5.0	3.16	0.76
Meat and bone meal	24	9.6	0	71	1.63	50.0	50	5.0	5.50	1.40
Soybean meal, expellers	14	5.6	0	85	1.98	47.5	45	3.0	0.68	2.00
Soybean seeds, raw	12	4.8	0	91	2.16	42.8	75	3.0	0.65	1.80
Soybean seeds, roasted	12	4.8	0	94	2.18	42.8	50	5.0	0.65	1.80
Mix[3]	12	4.8	0	77	1.78	62.2	38	5.3	1.20	1.22

[1]FU = Fill units, feed NDF weighted by particle size and the rumen degradability of those particles, RU = roughage units, NDF weighted by particle size and the effectiveness of fiber in stimulating chewing, ADIP = acid detergent insoluble protein.

[2]Forage characteristics vary with maturity and losses; values given represent typical or average values. The FU and RU were determined assuming that the portion of large particles was 80% for pasture, 50% for alfalfa, 70% for grass silage, 50% for small grain silage, and 50% for corn silage. The NDF concentration in small particles was 53% for pasture, 21% for alfalfa, 50% for grass, 25% for small grain silage, and 20% for corn silage.

[3]A protein mix consisting of 50% heat-treated (expellers) soybean meal, 25% blood meal, and 25% fish meal.

ments were assumed to be small particles, with a fill factor similar to that of alfalfa leaves and the grain in corn silage. Initial values were tested and refined in the model. The final values selected (Table 4) gave equivalent milk production with each forage in diets balanced to similar NDF concentrations.

The second limitation of the NRC system for formulating rations was related to the minimum fiber requirement. If the DMI constraint recommended by the NRC (23) is set as a maximum, a linear programming matrix can allow rations to be formulated that have lower DMI and higher NE_L density than recommended by the NRC

TABLE 4. Fill and roughage factors assigned to large and small particle pools of each feed type.

	Fill factors		Roughage factors	
	Large particles	Small particles	Large particles	Small particles
Alfalfa hay and silage	1.35	0.4	1.0	0.6
Grass hay and silage	1.50	0.8	1.0	0.8
Pasture	1.40	0.5	1.0	0.7
Corn silage	1.45	0.4	1.0	0.7
Small grain silage	1.55	0.6	1.0	0.8
Grain and concentrates	—	0.4	—	0.4

(23). Minimum fiber is recommended by the NRC (23) to prevent the NE_L density from going too high, which results in health disorders and milk fat depression. Reducing the particle size of fiber can reduce or eliminate its ability to meet the minimum fiber requirement.

A roughage unit (**RU**) system was used to ensure that adequate forage was included in rations. In addition, DAFOSYM has the option of selecting rations that minimize forage use when forage is not available or when it is expensive. Roughage units were then used to define the minimum forage allowed in rations.

The RU system again considered particle size and the NDF concentration of feeds (18). The equation used to estimate RU for each feed was:

$$RU_i = (RFL_i)\ (NDFL_i)\ (LP_i) + (RFS_i)\ (NDFS_i)\ (SP_i) \quad [10]$$

where RFL_i = RU factor of large particles in feed i, and RFS_i = RU factor of small particles in feed i.

Values for RFL and RFS were assigned to represent the relative physical effectiveness of the NDF in the two particle size pools. The effectiveness of NDF in long grass hay was assigned a value of 1.0, and chewing activity was used to estimate the relative physical effectiveness of the NDF in other forages (18). Large particles in all forages were assigned a roughage factor of 1.0. Factors for small particles were assigned so that the weighted average of the two particle pools provided values similar to the physically effective NDF values assigned by Mertens (18).

Fill and roughage units vary with the characteristics of the feed. This is particularly true for forages when large particle content (stem or stover portion) and NDF concentration in those particles vary with growing, harvest, and storage conditions (24). Typical FU and RU values for feeds are listed in Table 3. Although fill and roughage factors may be influenced by crop maturity and harvest method, this was not considered in the present model. Assigned factors represented typical or normal conditions.

Feed Allocation

A feed allocation scheme was developed that represented a producer's approach to making the best use of homegrown feeds. This scheme used decision rules to prioritize feed use. Optimal allocation through a linear programming approach was not used because it did not represent current feeding strategies on most dairy farms.

The feeds potentially available for use included any combination of: high-quality silage, low-quality silage, high-quality hay, low-quality hay, grain crop silage, high-moisture grain, and dry grain. Possible purchased feeds included corn grain, dry hay, a CP supplement, an RUP or oilseed supplement, and an animal or vegetable-based fat supplement. Because overfeeding ingredients such as animal fat, blood meal, and meat and bone meal could result in unpalatable diets, user-defined limits prevented excessive inclusion of these feeds in rations. In DAFOSYM, high-quality forage was that harvested with an NDF concentration less than a user-defined level (24, 25). Depending on growing and harvest conditions, differences in the average nutrient concentrations between high- and low-quality forages were often small.

The preferred forage for lactating cows was a mix of grain crop silage, high-quality alfalfa or grass silage, and high-quality hay. For nonlactating cows and growing heifers, preferred forages were grain crop silage, low-quality alfalfa or grass silage, and low-quality hay. Alternative forages were used when preferred forage stocks were depleted. If grain crop silage was not available, alfalfa or grass provided the forage. If high-quality hay or silage was preferred but unavailable, low-quality hay or silage was used and vice versa. When stocks of farm-produced forage were depleted, purchased hay was used.

A priority order for allocation was used to match forage quality with the animal group that best used the available nutrients. Feeds were allocated first to animals with low nutrient requirements (nonlactating cows and heifers) using low-quality forage. After that, the high-quality forage was allocated to the early lactation cows to maximize their production. Feeding the lower producing cows last allowed low-quality forage to be used by animals with lower nutrient requirements when stocks of high-quality forage were depleted. Similarly, feeding younger heifers after nonlactating cows and older heifers assured that, if a shortage of low-quality forage existed, animals with higher requirements received the better feed.

The portion of each forage used in rations was based on the amount of each forage type available and an estimate of the total forage requirement for the herd. Both available forage and forage requirement were modeled with FU. A total forage FU requirement for the herd was proportional to the sum of the maximum FU requirements of the individual animal groups:

$$AFR = \Sigma\ FR_j\ (FIC_j)\ (BW_j)\ (365\ d/yr)\ (\text{number of animals in group}) \quad [11]$$

where AFR = annual forage requirement for the herd, FU/yr, FIC_j = fiber ingestive capacity for animal group j, FU/kilogram of BW/d, BW_j = average BW in animal group j, kilograms, and FR_j = portion of the maximum FU that normally comes from forage for animal group j.

Values of FR_j varied among animal groups and with the amount of forage used in diets. Through a series of model runs, suitable values were determined that adequately predicted forage requirement over a range of diets. Average FR values determined for nonlactating cows, older heifers, and young heifers were 0.80, 0.80, and 0.98, respectively. For maximum forage rations, values of FR_j for early-, mid-, and late-lactation groups were 0.83, 0.90, and 0.93, respectively. For minimum forage rations, these values were 0.80, 0.68, and 0.57.

The objective in proportioning forage was to give first priority to pasture and second priority to silage. The lowest priority was given to dry hay because it was the easiest to market. Total fill units available from each forage source were determined as the product of the available forage DM and the FU concentration in that forage. When available, grazed forage was used to meet as much of the annual forage requirement as possible. The portion of grazed forage permitted in the diet was limited to that available in the pasture when distributed among the grazed animal groups.

The portion of each forage used to meet the remaining forage requirement was set by the ratio of the FU available in that forage to the total FU of all available forages. After the portions of pasture and ensiled feeds in the ration of a given animal group were set, the remaining forage requirement was met with dry hay. This procedure maximized the use of ensiled feeds, so that excess forage was normally dry hay. An additional option forced a user-defined, minimum amount of dry hay into rations even if it was not produced on the farm. This option enabled the modeling of farms that used a practice of feeding 10 to 15% of diet DM as hay.

Once a ration was formulated, the final step was to determine the number of animals in the group that could be fed that ration for a given time from current feed stocks. The period was a full year for confined feeding systems, but 1 mo for grazing animals. If feed stocks did not allow all animals in the group to be fed the given ration for the full period, as many animals as possible were fed. Remaining animals of the group were fed rations balanced with alternate feeds. If milk production within the group was different because different rations were used, a weighted average milk production was computed for the group. Remaining feed quantities were updated each time a group of animals was fed.

Animal Requirements

Rations for a representative animal of each animal group were formulated to meet 1) a minimum roughage requirement, 2) an energy requirement, 3) a minimum requirement of RDP, and 4) a minimum requirement of RUP. The minimum roughage requirement stipulated that the total roughage units in the diet had to meet or exceed 21% of the total ration DM (17, 18). This assured that roughage in the formulated ration was adequate to maintain proper rumen function.

The energy requirement for each animal group was determined by using relationships published by the NRC (23) with only minor alterations. For cows, the NE_L requirement was the sum of the requirements for maintenance, lactation, pregnancy, and BW gain or loss (23). The NE_L needed for lactation was increased by a lead factor to ensure that the energy requirements of a greater than average portion of the cows in each group were met (30). A lead factor of 12% was used for the early lactation group, and 7% was used for the mid- and late-lactation groups.

Maintenance energy was based on an animal in its third or higher lactation cycle. The total NE_L requirement was adjusted by the multiple of maintenance of the animal group to model the efficiency of energy use as influenced by DMI. The multiple of maintenance was the ratio of the total NE_L requirement to that for maintenance (Table 5). The total NE_L requirement was reduced by 4% for each multiple of maintenance less than three and increased by 4% for greater multiples of maintenance (23). Although increased intake actually affects the amount of energy extracted from the feed, this effect was included on the requirement side of the constraint equation to simplify the linear programming matrix (Table 5). Maintenance energy requirement was increased an additional 15% for grazing animals to account for their increased activity (23).

Finally, the NE_L requirement was increased to include an energy cost for excess protein in the diet (23). Each kilogram of excess protein required 0.7 Mcal of energy (as NE_L) to convert this protein to urea for excretion (32). Excess protein was computed to include both RUP and RDP (Table 5). Excess RDP was that greater than the amount useful for making bacterial CP (based on non-fat energy intake). Intake of RUP that caused total absorbed protein to exceed the absorbed protein requirement was considered excess.

The RUP requirement was the total absorbed protein requirement minus the digestible bacterial protein and the unavailable protein in the diet (Table 5). Total absorbed protein was the sum of maintenance, lactation, metabolic fecal, conceptus, retained, and absorbed tissue protein (23). The digestible bacterial protein was bacterial CP multiplied by a conversion efficiency of 64% (23). Unavailable protein in the diet was set at 70% of the ADIP in forages and 40% of that in concentrates (34). Because some of the ADIP of feeds was not

TABLE 5. Constraints and associated equations used to develop rations.

CONSTRAINT EQUATIONS[1]	
Maximum ingestive capacity	$\Sigma\, x_i(FU_i) \le FIC_j(BW_j)$
Minimum roughage requirement	$\Sigma\, x_i(RU_i - 0.21) \ge 0$
Energy requirement	
Mature cow	$\Sigma\, x_i(NEL_i) = [NELR_j + 0.7(ECP_j)]AMM_j$
Growing heifer	$\Sigma\, x_i\ 1.65(NEL_i) = MER_j + 0.7(1.65)(ECP_j)$
Minimum RUP requirement	$\Sigma\, x_i\ 0.87(AUP_i) \ge APR_j - 0.64(BCP_j)$
Minimum rumen ammonia for microbial growth	$\Sigma\, x_i(CP_i)(RPD_i + 0.15) \ge BCP_j \div 0.9$
ASSOCIATED EQUATIONS	
Adjustment for multiple of maintenance	$AMM_j = 0.92 \div [1. - 0.04(NELR_j \div NELM_j - 1.)]$
Available undegraded protein	$AUP_i = CP_i[1. - RPD_i - UF_i(ADIP_i)]$
Bacterial CP	
Mature cow	$BCP_j = 6.25\ (0.01)\ [NELR_j - x_{fat}\ (NEL_{fat})]$
Growing heifer	$BCP_j = 6.25\ (0.02)\ (BTDN_j)$
Excess CP	$ECP_j = \{\Sigma\, x_i\ (0.90)\ (CP_i)(RPD_i + .15) - BCP_j\} + \{\Sigma\, x_i(0.87)(UP_i) - [APR_j - .64\ (BCP_j)]\}$

x_i = Amount of feed i in the diet of animal group j (kilograms of DM/d),
x_{fat} = Amount of supplemental animal or vegetable fat in the diet of animal group j (kilograms of DM/d),
FU_i = Fill units of feed i (fraction of DM),
FIC_j = Fiber ingestive capacity for animal group j (fill units/kg/d),
BW_j = Animal BW in animal group j (kg),
RU_i = Roughage units of feed i (fraction of DM),
NEL_i = NE_L in feed i (Mcal/kg),
AMM_j = Adjustment factor for multiple of maintenance in lactating animal group j,
CP_i = CP concentration in feed i (fraction of DM),
$NELR_j$ = NE_L requirement of animal group j (Mcal/d), (23),
$NELM_j$ = NE_L requirement for maintenance of animal group j (Mcal/d), (23),
MER_j = Metabolizable energy requirement of heifer group j (Mcal/d), (23),
AUP_i = Available RUP in feed i (fraction of DM),
$ADIP_i$ = Acid detergent insoluble protein concentration in feed i (fraction of CP),
UF_i = Unavailable fraction of ADIP (0.7 for forages and 0.4 for concentrates),
BCP_j = Bacterial CP requirement of animal group j excluding energy from fat (fraction of DM),
$BTDN_j$ = Baseline TDN requirement of animal group j (kg/d), (23),
RPD_i = Rumen protein degradability of feed i (fraction of CP),
ECP_j = Excess CP (degradable plus undegradable) in the diet of animal group j (kg/d).

[1] Σ means the summation over all feeds in the ration.

included in the RUP, the ratio of digestible RUP to total RUP was set to 0.87 instead of the 0.8 recommended by the NRC (23).

The RUP requirement was rumen available protein minus rumen influx protein (Table 5). Rumen available protein was bacterial CP divided by a conversion efficiency of 90% (23). Bacterial CP was modeled as proportional to the NE_L in the ration (Table 5) which was a slight modification of the function documented by the NRC (23). Only energy coming from sources other than added fat was considered useful for making bacterial CP. Added animal or vegetable fat helped meet the energy requirement, but this added energy did not yield bacterial cells.

The P requirement was determined for each animal group by using relationships from NRC (23). This requirement set the minimum P intake of each animal group, and it was used to estimate the purchase of mineral supplements. Mineral supplements included phosphate, salt, and other minerals. Phosphate required was modeled as 5.3 times (assuming a 19% P concentration) the difference between the P requirement and the P contained in feeds summed over all animal groups. Phosphorus in each feed was the user-defined P concentration times the DM fed. The quantity of salt and other minerals fed was modeled as 0.5% of the total feed DM consumed.

Linear Program and Constraint Equations

Animal diets and performance were modeled with a linear program that simultaneously solved five constraint equations in a manner that maximized herd milk production with minimum cost rations. The constraints included a limit on ruminal fill and constraints for each of the four requirements described above. The ruminal fill limit was the product of the fiber ingestive capacity and the average animal weight for the given animal group (16). Thus, the sum of the fill units of the feeds in the ration had to be less than or equal to this maximum ingestive capacity (Table 5). The second constraint was the roughage requirement. As described above, the sum of the roughage units of all feeds in the diet had to be greater than 21% of the ration DM (Table 5).

The third constraint equation was that the energy consumed had to equal the energy requirement. An equality was used to ensure that energy balance was maintained and that intake and feed budgets were accurate for each animal group. The total NE_L from all feeds in the ration minus the energy cost of excess dietary protein had to equal the requirement (Table 5). The energy cost of excess protein placed some feed characteristic terms on the requirement side of the equation. To simplify the linear programming matrix, the equation was rearranged so that all feed characteristics were on the left side of the constraint equation. For growing animals, the requirement was based on metabolizable energy (Table 5). The metabolizable energy content of feeds was assumed to be 65% greater than the NE_L content (23).

The last two constraints specified the minimum protein requirement in the ration. The RUP constraint required that 87% of the sum of the RUP in all feeds had to be greater than or equal to the total absorbed protein requirement minus the bacterial CP production (Table 5). The RDP constraint required that the sum of the RDP contents of feeds plus the rumen influx protein (15% of feed CP) be greater than or equal to the rumen available protein requirement (Table 5). Because added fat did not aid the formation of bacterial CP and because the RUP requirement was affected by bacterial CP coming from RDP, feed characteristic terms were included on the right side of the protein constraint equations listed in Table 5. To simplify the linear programming matrix, the constraint equations were rearranged to move all feed characteristic terms to the left side of the equations.

The five constraint equations were simultaneously solved with the objective of minimizing ration cost. Ration cost was determined by using relative prices of feed ingredients. For grain and concentrates, the relative price was the long-term average price set by the model user. For forages, the relative price was set to zero for maximum forage diets. With a low relative price, the model used as much forage as possible in ration formulation. Another user-defined option allowed a minimum forage diet for lactating animals. For this option and these animal groups, the price of forage was set high relative to concentrate forcing a minimum amount of forage in rations.

The constraint equations were solved for each of the six animal groups making up the herd. Each solution provided a ration that met the minimum roughage, minimum protein, and energy requirements without exceeding the limit for intake. If a feasible solution was not found for early lactating animals, the milk production goal for the group was reduced by 0.5%, and the procedure was repeated until a feasible solution was found. For later lactation groups, milk yield predicted by the functions of Table 1 was reduced in proportion to the decrease found in early lactation. A set of feasible solutions for all animal groups, therefore, gave both balanced rations and a herd production level. Milk production was the maximum that could be achieved considering the nutritional value of available forage and the type and amount of concentrates used.

Manure DM and Nutrient Production

Manure production included fecal DM, urine DM, bedding, and feed lost into manure. Fecal DM was the total quantities of all feeds consumed by each animal group multiplied by the fraction of indigestible nutrients (1 − TDN) of each feed. The TDN values were reduced 4% for the low-production group and 8% for the medium- and high-production groups to account for the reductions in digestibility under multiple increases of intake over maintenance intake. Urinary DM was set as 5.7% of total urine, with a wet feces-to-urine ratio of 1.2 for heifers and 2.2 for cows (22). Manure DM was increased by the amount of bedding used and by an additional 3% of the feed DMI to account for feed lost into the manure. The quantity of wet manure was determined as manure DM divided by a user-defined value for manure DM content.

The nutrients in fresh manure were determined through a mass balance of the six animal groups. Manure nutrients equaled nutrient intake minus the nutrients contained in milk produced and animal tissue growth. Nitrogen intake was determined from the protein content of the feeds consumed (CP ÷ 6.25). Phosphorus and K intakes were set as the greater of the sum of that contained in feeds or the requirement of the animal group. For lactating animals, P supplementation above the quantities contained in feeds was often required; thus, P intake was normally based on animal requirements. Potassium supplementation was normally not required, so K intake was that contained in consumed feeds. Fractions of the three nutrients (N, P, and K) contained in milk and body tissue were set as average values for the herd. Nutrient concentrations were 0.53% N, 0.10% P, and 0.15% K for milk and 2.75% N, 0.79% P, and 0.20% K for body tissue (21, 23). Body tissue produced was based on animal mass exported from the herd, not the change in BW of individual animals during their annual cycle. Although these nutrient concentrations may vary with animal and feeding conditions, average values provided an acceptable level of detail for this model.

Manure N was partitioned between organic N and ammonia N. Organic N was assumed to come solely from feces. Fecal N was fecal protein divided by 6.25 where fecal protein was the sum of the indigestible bacterial protein, the indigestible nucleic protein, the indigestible undegraded protein, and the metabolic fecal protein (23). Fecal protein for the herd was the product of the fecal protein for each feeding group, the number of animals in the group, and the length of the feeding period summed over all animal groups. Eighty percent of the fecal N was assumed as organic N, and all remaining N was ammonia N. Organic N was considered stable during manure handling, and ammonia N was susceptible to volatile loss (5).

RESULTS AND DISCUSSION

Model Evaluation

Four procedures were used to verify that the dairy herd submodel worked properly and produced reasonable results. Nutrients in rations predicted by the model were first compared to requirements recommended by NRC (23). Next, diets formulated by the model for each animal group were compared to those formulated by the Spartan Dairy Ration Evaluator/Balancer (33). Manure excretion predicted by the model was then compared to measured data compiled by Wilkerson et al. (35). Finally, the binding constraints in the linear program were examined under different feeding scenarios.

Ration nutrients and animal requirements. Daily amounts of DMI, NE_L, and the minimum RUP and RDP required in rations were determined for a herd with the dairy herd submodel. The herd was composed of average-sized Holstein animals with an annual milk production of 9070 kg per cow. Characteristics determined by the model for the six animal groups included milk production, milk fat content, BW, and change in BW (Table 6). These characteristics for each animal group were then used to determine the NRC (23) recommended nutrient requirements (Table 6). The NRC recommendations for lactating animals were based on a second-lactation animal to represent the mix of primiparous and multiparous animals in the herd.

Nutrient amounts in the rations formulated by the dairy herd submodel showed reasonably close agreement with the NRC (23) recommendations. Dry matter intakes predicted by our model were about 15% less than those from the NRC for the nonlactating cow group. This occurred because the predicted energy requirement was low for this group and because the forage used in our analysis contained corn silage. With this high-energy forage, requirements for this group were met with a lower intake. Intakes for all other animal groups were within 5% of NRC recommended levels.

Net energy in the rations generated by the dairy herd submodel were within 1% of NRC recommendations (23) except for the nonlactating cow group (Table 6). The requirement for this group was 5% less than the NRC value. This was due to our adjustment to the

TABLE 6. Comparison of animal intake and requirements generated by the dairy herd submodel with those recommended by the NRC (23) for six animal groups representing average-sized Holsteins with an annual milk production of 9070 kg per cow.

Animal group	Milk production[1]	BW	BW change	DMI	Energy[2]	RUP	RDP
	(kg/d)	(kg)	(g/d)	(kg/d)	(Mcal/d)	(kg/d)	(kg/d)
Early lactation							
Herd submodel	37.7	592	–754	19.8	34.3	1.28	1.81
NRC				19.6	34.3	1.10	2.04
Mid lactation							
Herd submodel	35.6	593	244	21.1	36.0	1.29	1.92
NRC				20.6	35.6	1.11	2.13
Late lactation							
Herd submodel	23.2	650	508	18.6	29.5	1.07	1.65
NRC				19.3	29.5	1.02	1.72
Nonlactating cow							
Herd submodel	0.0	718	637	12.0	16.9	0.56	1.00
NRC				14.1	17.7	0.56	0.96
Older heifer (18 mo)							
Herd submodel	0.0	470	600	9.8	8.2	0.20	0.68
NRC				10.1	8.1	0.18	0.73
Younger heifer (7 mo)							
Herd submodel	0.0	198	730	4.8	4.4	0.23	0.35
NRC				4.7	4.4	0.28	0.27

[1]Milk fat content was 3.9, 3.3, and 3.8% for early, mid, and late lactation groups, respectively.

[2]Net energy of lactation for all older animal groups; metabolizable energy for heifer groups.

energy requirement for multiples of maintenance less than or greater than three. The nonlactating cow group was affected most because of their relatively low multiple of maintenance compared with lactating animals.

Minimum requirements of undegradable and degradable protein predicted by our model were also very similar to NRC recommendations. The RDP requirements predicted by our model were slightly less for lactating cows and greater for young heifers than those of the NRC (23). The RUP requirements were slightly greater for lactating cows and less for young heifers. These differences were primarily due to the small change in the slope of the bacterial CP equations used in our model (Table 5). Overall, the comparison of the two models verified that our model formulated rations with DMI and nutrient requirements similar to NRC (23) recommendations.

Ration composition. Rations were generated for each animal group of this same herd with alfalfa hay, alfalfa silage, corn silage, ground corn grain, soybean meal, and a protein mix. The protein mix was 50% heat-treated soybean meal, 25% blood meal, and 25% fish meal. The forage portion of the ration consisted of 19% alfalfa hay, 42% alfalfa silage, and 39% corn silage. Both alfalfa hay and silage were high quality forages (21% CP and 40% NDF). Nutritive characteristics of other feeds were those listed in Table 3. Using the same forage mix and the same feed characteristics, rations were generated with the Spartan Dairy Ration Evaluator/Balancer (33). Relative prices ($/kg) used in formulating rations were 0.0 for forages, 0.12 for grain, 0.23 for soybean meal, and 0.40 for the protein mix. To correspond with the assumptions of our model, the Spartan model was set up to balance on the absorbed protein requirement, and protein supplementation was maintained close to that needed to meet requirements, i.e. overfeeding of protein was avoided.

Rations formulated by the two models were similar with only a few differences (Table 7). For the early- and mid-lactation cow, nonlacting cow, and older heifer groups, the mix of feeds and diet characteristics generated by the two models were very similar. In the late-lactation group though, the Spartan model met requirements using about 40% more forage and 40% less corn grain. This occurred because the Spartan model predicted a higher DMI. With greater intake, requirements were met with a lower energy concentration in the diet. When the DMI of the Spartan program was set to that predicted by our model, formulated rations were essentially the same. For young heifers, the Spartan model used 20% less forage and 50% more concentrate in the ration (Table 7). This occurred because the Spartan model predicted a 14% greater energy requirement for this animal group than that predicted by our model. Since our model agreed with that recommended by the NRC (23), no further adjustment was made. Overall, the comparison of rations generated by the two models supported that our model generated reasonable rations, similar to those obtained from a widely accepted ration-balancing program.

TABLE 7. Comparison of rations generated by the dairy herd submodel with those formulated by the Spartan Dairy Ration Evaluator/Balancer (33) for six animal groups representing average-sized Holsteins with an annual milk production of 9070 kg per cow.[1]

Animal group	Alfalfa hay	Alfalfa silage	Corn silage	Corn grain	Soybean meal	Protein mix[2]	DMI	Ration NDF	Ration Energy[3]	Ration CP	Ration RUP
	(kg/d)							(% of DM)	(Mcal/kg DM)	(% of DM)	
Early lactation											
Herd submodel	1.7	3.8	3.5	10.0	0.2	1.0	20.2	26.4	1.70	15.6	6.5
Spartan	1.8	4.0	3.8	9.5	0.8	1.0	21.0	27.0	1.69	16.6	6.7
Mid lactation											
Herd submodel	2.3	5.1	4.7	9.0	0.0	0.9	22.0	30.1	1.64	15.4	6.0
Spartan	2.5	5.4	5.0	8.4	0.1	0.9	22.3	31.1	1.62	15.6	5.8
Late lactation											
Herd submodel	2.4	5.2	4.8	5.7	0.0	0.0	18.7	34.0	1.58	15.9	5.9
Spartan	3.3	7.4	6.8	3.3	0.0	0.0	20.8	40.5	1.48	14.9	4.3
Nonlactating cow											
Herd submodel	2.3	4.9	4.6	0.2	0.0	0.0	12.1	45.3	1.41	16.4	4.8
Spartan	2.5	5.4	5.0	0.0	0.0	0.0	12.9	46.3	1.39	15.9	4.7
Older heifer											
Herd submodel	1.8	4.0	3.7	0.2	0.0	0.0	9.8	45.5	0.85	15.7	4.3
Spartan	1.8	4.1	3.8	0.0	0.0	0.0	9.7	46.3	0.83	15.9	4.1
Younger heifer											
Herd submodel	0.7	1.6	1.5	1.0	0.0	0.0	4.9	38.3	0.92	15.0	4.7
Spartan	0.6	1.3	1.2	1.5	0.2	0.0	4.7	33.4	1.05	15.0	4.9

[1]Characteristics of all feeds (CP, RDP, ADIP, NDF, NE_L, and TDN) were set the same in both models.

[2]A RUP mix consisting of 50% heat-treated (protected) soybean meal, 25% blood meal, and 25% fish meal.

[3]Net energy of lactation for all older animal groups; metabolizable energy for heifer groups.

TABLE 8. Comparison of manure production and milk N predicted by the dairy herd submodel with measured data (35). Values are expressed per 1000 kg of BW.

	DMI	N intake	Total manure	Feces[1]	Total excreta N	Fecal N	Urinary N	Milk N
	(kg/d)	(g/d)	(kg/d)	(kg/d)	(g/d)			
Cows averaging 20 kg/d of milk								
Model, maximum forage diet	33.1	873	108	74	603	316	287	259
Model, minimum forage diet	30.5	764	86	59	494	316	178	259
Measured	29.7	787	89	60	542	270	272	234
Cows averaging 14 kg/d of milk								
Model, maximum forage diet	23.6	632	89	61	496	237	259	125
Model, minimum forage diet	19.2	490	54	37	354	237	117	125
Measured	22.3	549	66	41	399	192	208	121
Nonlactating cows								
Model	16.9	442	58	40	418[2]	201	217	0
Measured	10.0[3]	254	35	15	237	77	160	0
Growing cattle								
Model	22.5	551	90	49	486	198	288	0
Measured	18.1	530	68	33	447	193	254	0

[1]For model predictions, feces DM was converted to wet matter assuming a DM content of 16%.

[2]Predicted N intake and excretion were high for this group because a substantial portion of the diet came from high-quality (high-protein) alfalfa silage.

[3]The average DMI for nonlactatng cows was at least 40% less than that recommended by the NRC (23). These nonlactating cows were fed rations formulated for lactating cows with DMI restricted to about 1% of BW (35).

Manure excretion. The adequacy of the manure component of the dairy herd submodel was checked by comparing predicted and measured DM and N excretions. The measured data was compiled from calorimeter studies performed over a 30-yr period at the Energy Metabolism Unit in Beltsville, Maryland (35). This data set was selected because it represented a large number of animals fed a wide range of diets. To model these animals, animal characteristics were set similar to the average characteristics reported for four animal groups: cows averaging 29 kg/d of milk, cows averaging 14 kg/d of milk, nonlactating cows, and growing cattle (35). Model predicted values of total manure excreted, feces excreted, total excreta N, fecal N, urinary N, and milk N were compared to measured values. This comparison was not intended to provide a formal validation of the model, but rather to illustrate that predicted excretions were representative of those of dairy animals.

Because a wide range of diets was used in the many trials of the energy metabolism studies, specific rations could not be duplicated by our model. Our model was used assuming a ration consisting of high-quality alfalfa hay and silage, corn silage, ground corn grain, and a high RUP mix (Table 8). The diets formulated by our model had CP concentrations similar to the average diet of the published data. For lactating animals, rations were formulated with both high and low forage to grain ratios. This provided a range for comparing feed DM and N intake (Table 8).

Our model predicted greater manure excretion than that reported when a maximum forage diet was modeled (Table 8). For a minimum forage diet, though, total manure and fecal production were less than the average of the measured data. Overall, the ratios of manure output per unit of feed input were very similar between the model and measured data. Manure production predicted by our model for lactating cows was also similar to the average manure production for dairy cows (86 kg/d per 1000 kg of BW) published in the American Society of Agricultural Engineers (**ASAE**) Standards (2).

For nonlactating cows and growing cattle, our model predicted substantially greater feed intake and manure output than the average of that measured. The average intake for nonlactating cows reported by Wilkerson et al. (35) was 6.8 kg/d, which was at least 40% less than that normally expected or recommended by the NRC (23). The nonlactating cows used in the energy metabolism studies were fed rations formulated for lactating cows with DMI restricted to about 1% of BW (35), which caused the very low intake. The manure production of nonlactating cows predicted by our model was similar to the ASAE value for growing beef cattle (58 kg/d per 1000 kg of BW; 2). Overall, manure production values from our model were representative of those expected for dairy animals.

Nitrogen excretion values were generally similar between our model and the measured data. Total excreta N predicted by our model was higher than that measured (35) for all animal groups when maximum forage diets of high quality (high protein) forages were used. With minimum forage diets, both N intake and N excreted were less than that measured. Ratios of excreted N to N intake were similar between the measured and modeled data within each animal group. Our model predicted fecal N values that were 15% greater than those measured in higher producing animals. In the nonlactating cow group, the difference was much larger (Table 8). Predicted N intake and excretion were high for nonlactating cows because a substantial portion of the diet came from high-quality alfalfa silage, which resulted in overfeeding protein. Urinary N values were generally similar to measured values. Predicted urinary N excretions were higher than measured values for high forage diets and lower for low forage diets. In general, differences in N excretion between predicted and measured values were proportional to differences in protein or N intake.

Linear program constraints. To further verify that the model was functioning properly, the binding constraint equations in the linear program were examined under various feeding scenarios. The five constraints were ruminal fill, roughage, energy, RUP, and RDP. Because an equality function was used in the energy constraint, this constraint was always limiting or binding in ration formulation. Other binding constraints varied with the age and stage of lactation of the animal group and the feeds fed.

Nutrient requirements were most easily met in the older heifer group. When forage high in CP was used in ration formulation, all constraints other than energy were exceeded. Thus, nutrient requirements were met without grain or protein supplementation. If low protein forage such as corn silage was used, the RDP constraint was binding and protein supplementation was required for a balanced diet. For younger heifers, the ruminal fill and protein constraints were sometimes binding depending on the type of feeds used. When the forage was high-quality alfalfa, only the fill and energy constraints were binding. With a lower protein forage, the RUP constraint became binding as well. If both RDP and RUP supplements were used in formulating the ration, both the RDP and RUP constraints could be binding with no overfeeding of protein in the diet. Generally under this scenario, intake was no longer limited by the fill constraint.

When nonlactating cow rations were formulated, the binding constraints were again primarily influenced by the quality of the forage. Physical fill was never a constraint except perhaps with very low-quality forage. With high-protein forage, nutrient requirements were met with intake constrained only by energy. As the protein concentration of the forage was reduced, the RUP constraint became binding and protein supplementation was required. If the forage was all corn silage and a high RUP supplement was used, the RDP constraint was also binding.

For lactating cows, either the fill or roughage constraint was binding along with the energy and RUP constraints. For maximum forage diets, fill was the limiting constraint, but for minimum forage diets, the roughage constraint was limiting. At the point where maximum potential milk production was achieved, the fill, roughage, energy, and RUP constraints were all binding. If both RDP and RUP supplements were used in formulating the ration, all five constraints could be binding with no overfeeding of protein in the diet.

Model Application

The dairy herd model was developed for integration with other farm component models to enable whole farm simulations. In particular, this submodel was incorporated in DAFOSYM (25). This integrated model provides a useful tool for whole-farm assessment of 1) alternative cropping systems, 2) feed supplementation strategies, 3) feed impacts on manure management, 4) alternative harvest and preservation practices, 5) supplemental feed use with grazing, 6) risk in feed production, and 7) other strategic alternatives in dairy production.

The dairy herd submodel has evolved with the development of NRC recommendations and the needs of the DAFOSYM model (4, 5, 25, 28). Farm-level evaluation of diverse cropping and feeding strategies has required model refinement as documented in this report.

The current version of the herd model incorporated in DAFOSYM was used to evaluate the effects of alternative protein supplementation strategies on farm performance, profitability, and nutrient loss to the environment (27). Use of more expensive RUP supplements reduced N loss from farms and increased farm profit. Compared to soybean meal as the sole protein supplement, addition of a high RUP feed in rations reduced the annual volatile N loss by 13 to 34 kg/ha of cropland dependent upon other management strategies used on the farm. The reduction in N leaching loss was small at about 1 kg/ha. The feeding benefits from including the more expensive supplement improved farm net return by \$46 to \$69/cow per year.

The integrated model was also used to evaluate the whole farm benefits of corn silage processing. Use of this technique modified harvest and storage processes, influenced the particle size distribution in the feed, and increased the NE_L available to the animal under most crop and harvest conditions (26). Simulation of representative farms with different management strategies showed that corn silage processing could increase milk production or reduce grain consumption providing an annual increase in farm net return of $5 to $100/cow.

Further development of the herd model is planned to incorporate improvements in the recommendations of the NRC. Work is under way to add a seasonal calving strategy, to develop better prediction of pasture intake, and to validate model predictions with real farm pasture, feed, and animal performance data.

A Windows® version of DAFOSYM is available from the Internet home page of the Pasture Systems and Watershed Management Research Laboratory (http://pswmrl.arsup.psu.edu). Instructions for downloading and setting up the program are provided on the web site.

SUMMARY

A dairy herd submodel was developed that describes animal characteristics, formulates feed rations, and predicts feed consumption, milk production, and manure excretion for a herd consisting of three groups of lactating cows, one group of nonlactating cows, and two groups of heifers. A procedure was developed that used FU and RU to relate DMI to feed nutrient content over many different feeds. An FU was the combined NDF of large and small particle pools in each feed adjusted for their relative rates of ruminal digestibility, and RU was the NDF of the particle pools adjusted for the physical effectiveness of the fiber. A feed allocation scheme was devised that provided a good match of the available forages to the forage requirement of each animal group. Feed intake and milk production were predicted with a linear program that solved constraint equations for ruminal fill and roughage, energy, RUP, and RDP requirements. The quantity and nutrient content of excreted manure was determined using the TDN and nutrient contents of the feeds fed and the animal nutrient requirements. The dairy herd model generated feed intakes, nutrient requirements, feed rations, and manure excretions similar to those commonly recommended or expected for the various animal groups. The herd model produces annual feed budget, milk production, and manure excretion information that can be linked with other farm component models to provide whole-farm simulations.

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