A beef herd model for simulating feed intake, animal performance, and manure excretion in farm systems[1]

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ABSTRACT: A beef herd submodel was created for integration with other farm components to form a whole-farm model capable of simulating a wide range of beef production systems. This herd submodel determined the best available feed or feed mix to meet the fiber, energy, and protein requirements for each of up to six animal groups on the farm. The groups comprised any combination of cows, nursing calves, young heifers, yearling heifers, stockers, and finishing cattle. Protein, energy, and mineral requirements were determined for each group using the Cornell Net Carbohydrate and Protein System, Level 1. Diets were formulated to meet these requirements with available feeds, and the resulting feed intake, growth, and manure DM and nutrient (N, P, and K) excretions were predicted. Required feed characteristics included CP, ruminally degradable protein, acid detergent insoluble protein, NDF, P, and K concentrations. Feed intake was predicted by considering energy intake, potentially limited by fill, and exceeding a minimum roughage requirement. Fill and roughage limits were functions of feed NDF concentrations adjusted to consider particle size distribution and the relative rate of ruminal digestibility or the physical effectiveness of the fiber. The herd submodel was verified to predict feed intakes, nutrient requirements, diets, and manure excretions similar to those recommended or measured for beef animals. Incorporation of the beef herd submodel with other farm components, including crop growth (alfalfa, grass, corn, small grain, and soybean), harvest, storage, feeding, grazing, and manure handling, provided the Integrated Farm System Model. This comprehensive farm-simulation model is a useful research and teaching tool for evaluating and comparing the long-term performance, economics, and environmental impact of beef, dairy, and crop production systems.

Key Words: Beef Herd, Farm, Model, Production System, Simulation

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Introduction

With tighter profit margins and increasing environmental constraints, strategic planning of farm production systems is becoming both more important and more difficult. Animal production is complex, with a number of interacting processes that include crop and pasture production, crop harvest, feed storage, grazing, feeding, and manure handling. Computer simulation provides a useful tool for integrating these processes to predict the long-term performance, environmental impact, and economics of production strategies. The Dairy Forage System Model (**DAFOSYM**) provides this type of tool for dairy farms (Rotz et al., 1999b). This model has been used to evaluate numerous options in dairy production including various cropping, harvest, storage, feeding, grazing, and manure handling strategies.

Several major modeling efforts have developed and applied beef production simulation models in the United States and Canada. These include the Alberta Beef Production Simulation System (Pang et al., 1999), a cow–calf model for Montana rangeland (Tess and Kolstad, 2000), a cow–calf operation in Nebraska (Werth et al., 1991), and an integrated production system in eastern Canada (Koots and Gibson, 1998). More comprehensive models include "SPUR" for simulating beef production in rangeland ecosystems (Carlson and Thurow, 1996) and "GRAZE" for simulating intensive production in humid climates (Loewer et al., 1987). The scope of the farm system is limited in each of these models, however, and nutrient management and its resulting effect on the environment are not addressed.

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Table 1. Breed-dependent animal characteristics and suggested values for the model

Animal characteristic	Breed						
	Holstein	Simmental	Limousin	Shorthorn	Hereford	Charolais	Angus
Mature cow shrunk BW, kg	680	720	650	670	650	760	650
Peak milk production, kg/d	15.0	12.0	9.0	8.5	7.0	9.0	8.0
Milk fat, %	3.5	4.0	4.0	4.0	4.0	4.0	4.0
Milk protein, %	3.3	3.8	3.8	3.8	3.8	3.8	3.8
Calf birth weight, kg	43	39	37	37	36	39	31
Genetic effect on thermal neutral maintenance energy requirement[a]	1.2	1.2	1.0	1.0	1.0	1.0	1.0
Genetic effect on fiber ingestive capacity[b]	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Genetic effect on body composition rate[c]	8.0	7.2	6.0	6.0	6.3	7.5	6.0

[a]Animal characteristic defined by Fox et al. (2004).
[b]Animal characteristic defined by Rotz et al. (1999a).
[c]Genetic parameter (theta) developed by Williams and Jenkins (1998).

Our objective was to create a more comprehensive beef farm model by developing and integrating a beef animal component with DAFOSYM. Specific objectives were to 1) develop a model that predicts nutrient requirements, feed intake, growth, and manure excretion for all animal groups making up a beef herd, and 2) verify and evaluate this component by comparing model predictions to other accepted models and production data.

Materials and Methods

To simulate beef production in a whole-farm system, a beef herd model was required for integration with other components of the existing DAFOSYM model (Rotz et al., 1999b). This new component required a level of detail and linkages with other farm components similar to those provided by the dairy herd model used in DAFOSYM (Rotz et al., 1999a). The beef herd model was organized in six sections to predict animal intake and performance on a monthly time step. First, the animal groups making up the herd are established, where one animal with the average characteristics of the group represents each group. Next, feed characteristics are set and available feeds are allocated to the animal groups. Each group's requirements for fiber, energy, and protein are then determined, and a linear program is used to find the least-cost, nutritionally balanced mix of available feeds that meet these requirements. The established nutrient intake is then used to predict growth and BCS. Finally, based on the diet fed, the quantity and nutrient contents of the manure produced are determined.

Animal and Herd Characteristics

The herd is described by some combination of six possible animal groups: cows, nursing calves, young heifers, yearling replacement heifers, stocker cattle, and finishing cattle. The cow group is a mix of primiparous and multiparous cows, and a weighted average of the characteristics of these groups is used to describe a representative animal for ration balancing and estimation of feed intake. Nursing calves receive at least a portion of their diet from their mother's milk. Calves remain in this group until they reach a user-specified weaning age. At this age, they become young replacement heifers and/or stocker cattle. When 1 yr old, the young heifers are transferred to the older heifer group. All females beyond those needed for replacement and all males are in the stocker group until they reach 70% of their final shrunk BW (**FSBW**). Animals of this size are moved to the finishing group until they reach FSBW.

The model user sets the initial number of cows, replacement heifers, stocker cattle, and finishing cattle on the farm. For nursing calves, the number is set at 4% more than the number of cows to account for twins minus an 8% mortality loss. When animals other than nursing calves transition to the next age group or are sold from the farm, their number is adjusted considering a 2%/yr mortality loss. The age of all growing animals is set each month based on the user-defined calving month.

Animal characteristics are described as a function of breed. Seven breeds are predefined: Holstein, Simmental, Limousin, Shorthorn, Hereford, Charolais, and Angus. The user can modify these characteristics or define another breed or crossbreed. The primary characteristics used to define a breed are the mature cow shrunk BW (**CSBW**), peak milk yield, calf birth weight, the genetic influence on maintenance energy requirement, the genetic influence on fiber ingestive capacity, and the genetic influence on body composition rate. Suggested values for these characteristics are listed in Table 1 for the primary breeds. The genetic influence on body composition rate is a breed specific parameter that controls the empty body, fat-free growth rate relative to the empty body growth rate (Williams and Jenkins, 1998; also see the Growth, Development and Condition subsection).

Shrunk body weight (**SBW**) and ADG are primary characteristics used to describe growing animals. Target weights are initially set for each growing animal group at each month of its life cycle. For replacement heifers and all animals prior to weaning, this weight goal is a function of age:

$$SBW = CBW + CSBW[1.0 - e^{-m\,(AGE)}] \quad [1]$$

where CBW = calf birth weight, kg; m = maturity rate, d^{-1}; and AGE = animal age, d. A maturity rate of 0.0019/d was used to allow heifers to attain a proper weight for calving (80% of CSBW) at 2 yr of age. For stocker cattle, a linear growth rate is assumed where the post-weaning ADG is the difference between their target weight entering the finishing stage (70% of FSBW) and their weaning weight divided by the days available for growth. This available time is set by the user as the backgrounding period. The ADG goal during finishing is also set by the user. An initial ADG is determined for the first month with this target gain decreased 10% each month until FSBW is reached. The initial ADG is set to provide the average gain requested by the user. If feed quality allows, this target ADG is met. If the feeds fed limit ADG, then ADG is reduced and the length of the finishing period is extended.

For growing animals, this target weight relationship sets the potential rate of gain for each month. If an implant treatment is used for stocker or finishing cattle, this potential rate of gain is increased 10%, and the target FSBW is increased 5%. If the feed quality fed in a given month inhibits this potential growth rate, the highest possible rate is established (to be discussed later). When feed quality improves in future months, compensatory gain allows the animal group to move back toward its target weight.

Cow target weights are set assuming a BCS of 5.5. At this condition, the SBW of primiparous animals is set at 80% of the breed's CSBW and that of multiparous animals is 91% of CSBW. When available feeds cause a negative energy balance for the cow group, weight loss occurs. This weight loss is regained in future months if the energy balance improves.

Milk production for primiparous and multiparous cows is a function of the time in lactation and the peak milk yield (Fox et al., 2004):

$$MY = n/(a\,e^{kn}) \quad [2]$$

where MY = milk yield during week n of the lactation cycle, kg/d; a = 1.0/(P·k·e); P = peak milk yield during the lactation, kg/d; k = shape parameter, 1.0/8.5 wk; and n = time since calving, wk. Breed-specific values for peak milk production, milk fat content, and milk protein content are included in Table 1. Milk production of primiparous cows is set at 74% of that of mature cows and production in the second lactation is 88% of that in later lactations (Fox et al., 2004).

A fiber ingestive capacity (**FIC**) is determined for each animal group during each month. The FIC is used to set a limit on the potential fiber intake (Rotz et al., 1999a). This ingestive capacity is the sum of the capacity as affected by body leanness and lactation (Tess and Kolstad, 2000):

$$FIC = (CAP_f + CAP_l)/SBW \quad [3]$$

where FIC = fiber ingestive capacity, % SBW/d; CAP_f = F(LN) (0.0148 + [0.0066{ALN − LN}/ALN]); CAP_l = 0.122 (MY); LN = Current lean (no fat) body mass, kg; and ALN = adult lean (no fat) body mass, kg = 0.8 (0.891) (FSBW).

The factor F represents the effect of carcass leanness, which is limited to a maximum of 1.0:

$$F = 0.8 + 0.2\ [0.36 - 0.0377(BCS)]/0.16 \quad [4]$$

Where BCS = BCS, nine-point scale.

The FIC is then adjusted to include effects for ionophore and implant treatments. Implants allow a 10% increase in FIC, whereas ionophore treatments cause a 3 to 6% decrease. Finally, FIC is multiplied by the parameter set by the model user as a breed characteristic to allow for genetic influences (Table 1).

Feed Allocation

A feed allocation scheme is used to represent a producer's approach to making the best use of homegrown feeds. This scheme uses decision rules to prioritize feed use. The feeds potentially available for feeding include any combination of pasture, high-quality silage, low-quality silage, high-quality hay, low-quality hay, grain crop silage, high-moisture grain, and dry grain. Purchased feeds can include grain, dry hay, a CP supplement, a ruminally undegradable protein (**RUP**) or oilseed supplement, and an animal or vegetable-based fat supplement. Because overfeeding of some feed ingredients may result in unpalatable diets, user-specified limits prevent excessive inclusion of supplemental feeds in rations. Harvested forage is classified as high or low quality relative to a user-specified NDF concentration (Rotz et al., 1989).

When an animal group is grazed, the preferred forage is always pasture. If ample pasture is not available to meet the needs of the grazing animal groups, each group is supplemented with at least one other forage. If grain-crop silage is available to a given animal group, this will be one of the forages fed; otherwise, it will be excluded from the forage mix. The next priority is given to grass or alfalfa silage with the lowest priority given to dry hay because hay is the easiest to market. Lower-priority forages are used when preferred forage stocks are depleted.

A priority order for allocation is used to match forage quality with the animal groups that best use the available nutrients. Feeds are allocated first to cows, if any are maintained on the farm. The next group fed is nursing calves followed by young heifers, older heifers, stocker cattle, and finally finishing cattle. High-quality forage (grass or alfalfa hay or silage) is the preferred forage for feeding calves and finishing cattle (unless pasture is used) to maximize their production. Lower-quality forage is normally fed to cows and stockers. These animals can be maintained with lower-quality forage, and if they lose condition from low-quality feed, they can recover more easily than other animal groups. If high-quality hay or silage is preferred but unavailable, low-quality hay or silage is used and vice versa. When stocks of farm-produced forage are depleted, purchased hay is used.

The portion of each forage used in rations is based on the quantity of each available and an estimate of the annual forage requirement for the herd. Forage quantities are measured in megacalories of NE_m to account for quality differences among forages. Thus, the annual forage requirement is estimated from the herd's total energy requirement (Mcal of NE_m) summed over all months of the year and all animal groups on the farm. Monthly requirements of each group are estimated from the number and type of animals in the group and the group average SBW and ADG. For all animals other than finishing cattle on a high-grain diet, the full energy requirement is assumed to be met with forage. For finishing cattle fed a high grain diet, the energy from forage is estimated as 10% of their total energy requirement. Total energy available from each forage source is the product of the available DM and the NE_m content in that forage.

When pasture is available, grazed forage is used to meet as much of the forage requirement as possible. The portion of grazed forage permitted in the diet is limited to that available on a given month when distributed among the grazed animal groups. If pasture is available to meet the entire forage requirement of all grazing animals for a given month, then this is the only forage fed to those animal groups. When pasture does not meet the full requirement, additional forage is obtained from conserved or purchased forage. This supplemental forage is distributed across animal groups as long as supplies last.

The portion of each forage type used to meet the supplemental forage requirement is set by the ratio of the total NE_m available in a given forage to the total NE_m of all available forages. If adequate quantities of silage are available to meet the remaining forage requirement, then a mix of available silages is used. After the portions of pasture and ensiled feeds in the ration of a given animal group are set, any remaining forage requirement is met with dry hay. This procedure maximizes the use of ensiled feeds so that excess forage is normally dry hay.

Allocation of feeds to nursing calves requires additional rules. During the calf's first 2 mo, energy and protein requirements are completely met by the mother's milk. After 2 mo, the calf begins to supplement its diet with other available feeds (primarily forage) to meet its requirements. The amount of supplemental feed consumed each month is that needed to make up the difference between the calf's energy and protein requirements and the nutrients available from the mother's milk. Available milk is determined from Eq. [2]. The forage allocated to calves follows the same allocation rules used for other animal groups. When pasture is available, it is used. If pasture is not available, high-quality forage is used.

Once a diet is formulated for a given animal group and month, the final step is to determine the number of animals in the group that can be fed that diet from current feedstocks. If these feedstocks do not allow all animals in the group to be fed the given ration for the full month, as many animals as possible are fed. Remaining animals of the group are fed diets balanced with alternate feeds. If ADG within the group is different because different diets are used, a weighted ADG is computed for the group. Remaining feed quantities are updated each time a group of animals is fed.

Animal Requirements

Diets for a representative animal of each animal group are formulated to meet four nutrient requirements: a minimum roughage requirement, an energy requirement, a minimum requirement of ruminally degradable protein (**RDP**), and a minimum requirement of RUP. The minimum roughage requirement stipulates that the total roughage units in the diet must meet or exceed 20% of the total ration DM (Mertens, 1992 and 1997). For finishing cattle fed a high-grain diet, this minimum roughage requirement is decreased to 12%. This assures that roughage in the formulated ration is adequate to maintain proper ruminal function with at least 20% of the finishing diet DM coming from forage.

The energy and protein requirements for each animal group are determined using relationships from the Cornell Net Carbohydrate and Protein System, level 1 (**CNCPS**; Fox et al., 2004). The energy requirement is the sum of the requirements for maintenance, lactation, pregnancy, and growth. For lactating cows, energy can also be available from weight loss. The maintenance energy requirement is determined as influenced by lactation, activity, and ambient temperature (Fox et al., 2004). The lactation effect is determined using a thermal neutral maintenance requirement for fasting metabolism of 0.07 Mcal/(d·$SBW^{0.75}$), but this requirement can be adjusted using a multiplier entered as a breed characteristic (Table 1).

Activity is modeled as the sum of the daily requirements for standing, changing position, and distance traveled (Fox et al., 2004). Hours spent standing is set at 12, 14, 16, and 18 h/d for confinement, half-day intensive grazing, full-day intensive grazing, and continuous grazing, respectively. Distances traveled for these four options are 0.5, 0.8, 1.0, and 1.2 km/d, respectively. A temperature effect and the resulting potential for heat stress are a function of the current and previous month's average temperature and the current relative humidity, wind speed, and hours of exposure to sun

Table 2. Constraints of the linear program used to balance beef diets[a]

Constraint equations	
Physical fill	$\Sigma x_i (FU_i) \leq (FIC) (SBW)$
Effective fiber	$\Sigma x_i (RU_i) \geq (EF) (DMI)$
Energy	$\Sigma x_i (NEM_i) = (NEMD) (DMI) + 0.7 (EP)$
Ruminally degradable protein	$\Sigma x_i (CP_i) (DEGR_i + 0.15) \geq MCP/0.9$
Ruminally undegradable protein	$\Sigma x_i\ 0.87 (CP_i) (1 - DEGR_i - UP_i) \leq MPR - 0.64 (MCP)$
Associated equations	
Excess protein	$EP = \Sigma x_i (CP_i) [DEGR_i + 0.15 + 0.87 (1 - DEGR_i - UP)] - MPR + 0.47 (MCP)$
Microbial CP	$MCP = 0.13 (TDND) (DMI)$
TDN of diet	$TDND = 0.31 (NEMD) + 0.2$

[a] CP_i = CP concentration in feed i, fraction of DM; $DEGR_i$ = ruminal degradability of protein in feed i, fraction of CP; DMI = DMI estimate that resolves NE_m intake with NE_m and NE_g requirements, kg/d; EF = effective fiber requirement (0.12 for finishing cattle on high-concentrate diet and 0.20 otherwise), fraction of diet DM; EP = excess protein consumption, kg/d; FIC = fiber ingestive capacity, kg NDF·kg $SBW^{-1}\cdot d^{-1}$; FU_i = fill units (NDF adjusted for particle size and digestibility; Rotz et al., 1999a) of feed i, fraction of DM; MCP = microbial CP production, kg/d; MPR = metabolizable protein requirement, kg/d; NEM_i = NE_m concentration in feed i, Mcal/kg DM; NEMD = diet NE_m that resolves NE_m intake with NE_m and NE_g requirements, Mcal/kg DM; RU_i = roughage units (NDF adjusted for particle size and digestibility; Rotz et al., 1999a) of feed i, fraction of DM; SBW = shrunk BW, kg; TDND = TDN concentration of the diet, fraction of DM; UP_i = unavailable protein in feed i, fraction of CP; and x_i = quantity of feed i in the diet, kg of DM/d.

light (Fox et al., 2004). Due to a relatively minor sensitivity to relative humidity and wind speed, they are set at average values of 40% and 1.6 km/h, respectively. Sun exposure time is set at 0, 5, and 10 h/d for confinement, half-day, and full-day grazing systems. Cold stress is modeled considering an average hide thickness and hair coat (Fox et al., 2004), but this stress seldom occurs using temperatures averaged over a monthly time step.

Cows also have an energy requirement for lactation, and both cows and replacement heifers have gestation requirements during pregnancy. The ME requirement for lactation is proportional to milk yield with an influence from milk fat content (Fox et al., 2004). The gestation requirement is a function of the number of days pregnant and calf birth weight (Fox et al., 2004).

Energy required for growth is a function of ADG and equivalent empty BW (Fox et al., 2004). To determine an equivalent empty BW, a standard reference weight is assumed. This standard reference weight is 478 kg for replacement heifers and 462 kg for all other growing animals. Cows in early lactation are allowed to lose weight to maintain milk production. Energy received from mobilized reserves is a function of weight loss and BCS (Fox et al., 2004).

Finally, the NE requirement is increased to include an energy cost for excess protein in the diet. Our model implementation required a different approach for the calculation of urea cost than that used by Fox et al. (2004). Each kilogram of excess protein is assumed to require 0.7 Mcal of NE to convert this protein to urea for excretion (Tyrrell et al., 1970). Excess protein includes both RUP and RDP (Table 2). Excess RDP is that greater than the amount useful for making microbial CP. Intake of RUP that causes total metabolizable protein to exceed the metabolizable protein requirement is considered excess.

The metabolizable protein requirement of each animal group is the sum of the maintenance, lactation, pregnancy, and growth requirements. The maintenance requirement is a function of SBW, lactation requirement is proportional to milk yield and milk protein content, gestation is a function of calf birth weight and days pregnant, and the growth requirement is related to ADG and the NE required for growth (Fox et al., 2004). The metabolizable protein requirement includes RDP and RUP requirements. The RDP requirement is the microbial CP required divided by 0.9, where microbial CP is defined as 13% of the diet TDN excluding TDN from added fat sources (NRC, 2000). The RUP requirement is the total metabolizable protein requirement minus 64% of the microbial CP requirement.

Mineral requirements considered in the model include P and K. The P requirement (g of P/d) for each animal group is the sum of the daily requirements for maintenance, lactation, gestation, and growth (NRC, 2000). The daily maintenance requirement is 0.016 g of P/kg of SBW. For lactating cows, the lactation requirement is 0.9 g of P/kg of milk yield. The daily gestation requirement is 7.6 g of P/kg of fetal weight gain over the last 90 d of pregnancy, and the growth requirement is 0.039 g of P/g of protein gain. The sum of the requirements is divided by an absorption coefficient of 0.68 (NRC, 2000). The K requirement of each animal group is set at 0.6% of DMI (NRC, 2000; Fox et al., 2004). These requirements set the minimum P and K intakes of each animal group, and the P requirement is used to estimate the purchase of mineral supplements (Rotz et al., 1999a).

Ration Balancing and Performance Prediction

Ration balancing and performance prediction is accomplished through an iterative solution, where a linear program is used to determine a least-cost ration that meets the nutrient requirements. Intake is energy driven, but it is potentially limited by physical fill. Constraints on the ration include physical fill, effective fiber or roughage, energy, degradable protein, and undegradable protein.

An iterative determination of DMI begins with an estimate of the NE_m concentration of the final diet. For most animal groups that are fed a predominately forage diet, NE_m of the final diet is estimated as the NE_m concentration in the forage or forage mix fed to the given animal group. If the group is finishing cattle fed a high-grain diet, the diet NE_m is estimated assuming that 90% of the diet energy will come from available grain with the remaining 10% from forage.

Based on the diet NE_m, diet concentrations of NEg and ME are determined. Over the range of realistic beef dietary energy concentrations ($0.8 < NE_m < 2.5$ Mcal/kg), NE_g and ME are linearly related to NE_m. The following functions were fit to data generated by calculating NE_g and NE_m over a range in dietary ME concentrations (NRC, 2000):

$$NE_g = 0.907\ (NE_m) - 0.458\ (r^2 > 0.999) \quad [5]$$

$$ME = 1.095\ (NE_m) + 0.751\ (r^2 > 0.999) \quad [6]$$

Total DMI for the animal group is the sum of the DMI for maintenance and that for gain. The DMI required for maintenance is the NE_m requirement divided by the estimated NE_m of the diet. The DMI required for gain is the net energy required to meet the ADG goal divided by the NE_g of the diet.

After DMI and the associated energy concentrations are established, a linear program is used to balance the ration. Five constraint equations are solved in a manner that maximizes herd production with minimum cost rations (Table 2). Constraints include ruminal fill and the effective fiber, energy, RDP, and RUP requirements. The ruminal fill limit is the product of FIC and SBW for a given animal group (Mertens, 1987). Thus, the sum of the fill units of all feeds in the ration must be less than or equal to this maximum ingestive capacity. Fill units are the NDF concentration of feeds adjusted for particle size and fiber digestibility effects (Rotz et al., 1999a).

An effective fiber constraint assures that diets formulated contain adequate amounts of roughage. The sum of the roughage units of all feeds in the diet must exceed the minimum roughage requirement (Table 2). The roughage unit content of each feed is the NDF concentration adjusted to represent effects of particle size and the physical effectiveness of the fiber (Rotz et al., 1999a).

The energy constraint requires the energy consumed to equal the energy requirement. Thus, the total NE_m from all feeds in the ration must equal the requirement plus the energy cost of excess dietary protein (Table 2). The energy cost of excess protein places some feed characteristic terms on the requirement side of the equation. To simplify the linear programming implementation, the equation was rearranged so that all feed characteristics were on the left side of the constraint equation.

The last two constraints specify the minimum protein requirement in the ration. The RUP constraint requires that the sum of the digestible RUP in all feeds must be greater than or equal to the total metabolizable protein required minus the microbial metabolizable protein (Table 2). Microbial metabolizable protein is microbial CP multiplied by a conversion efficiency of 64%, and total RUP is converted to digestible RUP considering a digestibility of 87%. The RDP constraint requires 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 RDP requirement (Table 2).

The five constraint equations are simultaneously solved with the objective of minimizing ration cost. Ration cost is determined using relative prices of feed ingredients. For grain and concentrates, the relative price is the long-term average price set by the model user. For forages, the relative price is set to zero for maximum forage diets. With a low relative price, the model uses as much forage as possible in ration formulation. Another user-specified option allows for a minimum forage diet for finishing cattle. For this option, the price of forage is set high relative to concentrates forcing a minimum amount of forage in rations.

The constraint equations are solved by the linear program to provide a ration that meets the minimum roughage, minimum protein, and energy requirements without exceeding the limits on DMI. If a feasible solution is not found for growing animals, the ADG for the group is decreased by 5% and the procedure is repeated until a feasible solution is found. If a feasible solution is not found for lactating cows, their BW loss (and resulting BCS) is increased by 50 g/d and the procedure is repeated until their energy need is offset by energy obtained from mobilized reserves.

The solution from the ration-balancing linear program provides a better estimate of the energy concentrations in the diet and the DMI. If the DMI obtained based on the formulated diet is not within 1% of the initial estimate, a new set of requirements is determined using the new estimated DMI. This iterative process is repeated until the difference between the estimated and final DMI is less than 1%.

A final iteration is implemented if the user specifies that minimal grain should be fed. If grain is included in the feasible solution, then animal gain is decreased and another feasible ration is determined. This procedure is continued until a ration is obtained without using grain or until a minimum allowable gain is reached. This minimum gain is set at 10% of the initial target gain. At this point, grain is allowed in the ration to prevent adverse long-term effects on animal productivity. When gain is decreased on a given month due to low feed quality, the potential gain for following months is increased to allow compensatory gain to bring the animal group back toward its target weight. A set of feasible solutions for a given month of the year gives balanced rations, feed intakes, and weight changes for all animal groups. This solution makes good use of available feeds, while maintaining an acceptable production level.

Growth, Development, and Condition

The ADG determined for each group of growing cattle on a given month is used to determine the SBW and BCS of that group for the next month. For cows, a loss in body reserves decreases BW and BCS for the following month. Weight for the next month is the current weight plus the weight change over the month (30.4 d).

Body composition and BCS of each animal group are predicted using the composition model of Williams and Jenkins (1998). Their model is implemented with the following assumptions or simplifications: 1) the stage of maturity for transition from growing cattle to mature cattle is 70% of FSBW rather than floating with the rate variable; 2) a monthly time step is used; 3) the lag term for effect of nutrition is set equal to average daily gain; 4) calves are assumed to be born at a BCS of 3; and 5) replacement heifers have target gain rates to achieve 60% of CSBW at breeding age (15 mo) and 80% of CSBW at calving (24 mo; NRC, 2000). Fat free weight (**FFW**) of each animal group is described as a function of maturity where the monthly change in FFW is influenced by a genetic effect on body composition rate (Williams and Jenkins, 1998; Table 1). During months when ADG is greater than the change in FFW, BCS increases. Likewise when ADG is less than the change in FFW, BCS decreases.

When growing animals progress to a suitable age or sufficient BW, they transition to the next age group. The animal characteristics entering the next group are set equal to those completing the current group. At this point, the number of animals bought or sold is determined. If the number of animals specified for the next age group is greater than the number in the current group less mortality loss, then the difference is purchased. If the number specified for the next group is less than the current number minus loss, the difference is sold. If all animals entering a group are purchased, their characteristics are set assuming a target weight and condition. The number, month of the year, SBW, and BCS of the animals bought or sold are tracked for use in determining the cost of purchased animals and the income from animal sales (Rotz and Coiner, 2003).

Manure DM and Nutrient Production

Manure DM production is the sum of the DM from feces, urine, bedding, and feed lost into manure. Fecal DM is the total quantity of all feeds consumed by each animal group multiplied by the fraction of indigestible nutrients (1 – TDN) of each feed. Urine production (kg/d) is predicted as a function of DMI, CP intake, and milk production (Fox et al., 2004):

$$\mathrm{URINE} = [3.55 + 0.16(\mathrm{DMIA}) + 6.73(\mathrm{CPIA}) - 0.35(\mathrm{MILKA})]\ \mathrm{SBW}/454; \quad [7]$$

where DMIA = DMI per 454-kg animal unit, kg/d; CPIA = CP intake per 454-kg animal unit, kg/d; and MILKA = milk production per 454-kg animal unit, kg/d. Urinary DM is set as 5.7% of total urine. Additional manure DM includes any bedding DM used and 3% of the feed DMI (excluding pasture) that is lost into the manure.

The nutrients in fresh manure are determined for each simulated month through a mass balance of the six animal groups. Manure nutrients tracked are N, P, and K. The quantity of each nutrient excreted is the nutrient intake minus the nutrients contained in animal tissue growth and that excreted in milk. Nitrogen intake is determined from the protein content of the feeds consumed (CP/6.25). Phosphorus and K intakes are set as the greater of the sum of that contained in feeds consumed or that required by the animal group. Through a user-defined factor, the P requirement can be increased or decreased relative to the recommended level to represent the feeding practice of a simulated herd. Fractions of the three nutrients in milk and body tissue are set as average values for the herd. Milk N is determined from the milk protein content, which is related to the breed (Table 1). Remaining nutrient concentrations are 0.09% P and 0.15% K for milk and 2.75% N, 0.79% P, and 0.20% K for body tissue. Body tissue produced is based on animal mass exported from the herd (dead or alive) minus that imported. This provides a more accurate long-term balance than tracking the change in body weight of individual animals during each month of their annual cycle. Manure P and K from lost feed are set at 3% of the total intake of each nutrient, and organic bedding materials are assumed to contain 0.06% P and 2.4% K.

Manure N is partitioned between organic and ammonium N. Organic N is assumed to come primarily from feces. Fecal N is fecal protein divided by 6.25, where fecal protein is the sum of the undigested bacterial protein, the undigested feed protein, and the metabolic fecal protein (NRC, 1989; Fox et al., 2004). Undigested bacterial protein is defined as 26% of the microbial CP (Table 2) produced in the rumen. Undigested feed protein includes all acid detergent insoluble protein consumed in the animal diet plus the indigestible portion (13%) of the remaining RUP (diet RUP minus acid detergent insoluble protein). Metabolic fecal protein is 9% of the indigestible DM consumed (NRC, 1989). Manure organic N also includes N from feed lost into manure, N contained in bedding, and the N in scurf loss of hair and other tissue from animals. Feed loss is assumed to be 3% of the total N intake, and the N from organic bedding materials is 0.69% of the bedding DM. Scurf loss of protein (SPA) is a function of the BW of each animal group (Fox et al., 2004):

$$\mathrm{SPA} = 0.0002\ (\mathrm{SBW})^{0.6}/0.67 \quad [8]$$

Fecal and scurf N from the herd is the product of the excretions for each group, the number of animals in the group, and the length of the feeding period (30.4 d) summed over all animal groups. Urinary N excretion is then assumed to be the total N excreted by all animal groups minus the fecal and scurf N. Eighty percent of the fecal and scurf N is assumed to be organic N, and all remaining N (including all urine N) is considered to be ammonium or another N form that can readily transform to ammonia following deposition. Organic N is considered stable during manure handling, and ammonia N is susceptible to volatile loss (Rotz and Coiner, 2003).

Results and Discussion

The new beef herd component was integrated with the crop growth, harvest, storage, grazing, and manure-handling component models to form the Integrated Farm System Model (**IFSM**; Rotz and Coiner, 2003). The completed model was thoroughly evaluated to ensure reasonable and accurate predictions. This evaluation involved several phases. First, predicted nutrient requirements were verified for each major type of animal. Then, simulated feed intake and growth were compared to those measured in a field trial. Finally, three options in beef farming systems were simulated to further evaluate and demonstrate the use of the whole-farm model.

Requirement Verification

To verify animal nutrient requirements, values predicted by the herd model in IFSM were compared with those predicted by CNCPS (Fox et al., 2004). Although essentially the same relationships were used in both models, our implementation was slightly different. One of the primary differences was the prediction of the energy cost of excess protein in diets. Because of minor differences, values generated by the two models were not exactly the same.

Table 3 shows a comparison of values generated by the two models for DMI, ADG, and the ME, metabolizable protein, and P requirements. Comparisons were made for major animal types and ages, with the same animal and environmental characteristics and similar feed characteristics used in both models. When the DMI predicted by the IFSM model for each animal group was set in the CNCPS model, ME requirements predicted by the models were within 3%, and the predicted ADG was within 10% (Table 3). Minor differences in the maintenance energy requirement were caused by differences in the calculation of the energy cost of excess protein. Differences in the maintenance requirement created differences in the energy available for growth, which caused the small differences in ADG. Values generated by the two models for total energy, maintenance protein, and P requirements were essentially within rounding error. Differences in predicted ADG caused some differences in the protein required for growth and the total metabolizable protein requirement (Table 3). This comparison verified that the requirement functions from CNCPS were correctly implemented in IFSM and that IFSM would predict accurate rates of gain for a given feed intake and nutrient content fed.

Simulated Field Trial

Further evaluation was done to compare simulated and actual feed consumption and growth. Actual data were obtained from a field trial conducted from 1996 to 1998 near State College, PA (J. W. Comerford, H. W. Harpster, E. H. Cash, R. Stout, and R. L. Swope, unpublished results). One treatment from this experiment was used where 15 Angus and Angus crossbred cow–calf pairs were grazed and fed harvested forage all year from 19.9 ha of predominately orchard grass pasture. The trial included replications at two locations about 15 km apart. The average of these two replications was compared to a simulation of this treatment.

Parameters for the simulation were set to represent the experimental trial. Mature cow BW and calf birth weight were set to the average of the animals in the trial (680 kg and 44 kg, respectively). Nutritive contents of the pasture were set to represent the seasonal variation measured in the trial (Comerford et al., unpublished results). The trial was simulated over the 3-yr period using daily weather data measured near State College.

The model accurately predicted calf BW from birth to weaning (Figure 1). Although measured calf weights varied due to differences in gender and genetic traits, measured weights were well balanced around the model prediction. Measured weights were highly correlated (r^2 = 0.96) to those predicted by the model with a root mean square error of 15.9.

A comparison of simulated and measured forage production and utilization showed some differences, but this comparison also supported that the model could adequately represent the field trial (Figure 2). Ninety-five percent confidence intervals were 19.0, 9.4, and 17.8 t of DM for the grazed, fed, and residual forage production measurements, respectively. Thus, the simulated data fit well within the range of the measured values. The largest disagreement between simulated and actual pasture utilization occurred in 1996. Forage consumption measured during this year was 40% greater than that measured during the following years. Considering the animal mass fed over the full year, this forage consumption represented a high daily intake of approximately 2.8% of the animal BW. Thus, a portion of the discrepancy found in 1996 may have been due to experimental measurement error. Although the same procedure was used throughout the experiment, measurements in 1996 were made by a different person than those of the remaining two years. In addition, greater rainfall increased sward density in 1996, and may have influenced animal behavior.

Table 3. Verification of ADG and the requirements for energy, protein, and phosphorus predicted for various animal types by the beef herd component in the Integrated Farm System Model (IFSM) compared with values predicted by the Cornell Net Carbohydrate and Protein System (CNCPS)

					ME		Metabolizable protein		
Animal type[a]	Model	Shrunk BW, kg	DMI, kg/d	ADG, kg/d	Maintenance, Mcal/d	Total, Mcal/d	Maintenance, g/d	Total, g/d	P, g/d
Stocker, 8 mo old	IFSM	307	6.6	0.63	10.4	16.0	279	473	13
	CNCPS	307	6.6	0.67	10.0	16.0	279	486	13
Stocker, 12 mo old	IFSM	395	8.4	0.47	14.3	19.4	337	492	13
	CNCPS	395	8.4	0.51	13.9	19.4	337	502	14
Replacement heifer,	IFSM	457	8.0	0.51	15.3	20.2	376	541	15
16 mo old	CNCPS	457	8.0	0.53	14.9	20.1	376	547	15
Replacement heifer,	IFSM	549	12.0	0.35	18.7	30.3	431	749	21
23 mo old	CNCPS	549	12.0	0.38	18.4	30.3	431	757	21
Finishing cattle,	IFSM	549	8.9	0.89	15.4	25.7	423	726	18
16 mo old	CNCPS	549	8.9	0.86	15.7	25.7	423	715	18
Non lactating cow	IFSM	621	10.6	0.00	20.0	26.0	473	667	20
	CNCPS	621	10.6	0.00	19.8	25.7	473	668	20
Lactating cow	IFSM	621	11.7	0.00	22.3	29.9	473	863	23
	CNCPS	621	11.7	0.00	21.6	29.3	473	865	23

[a]All animals were Angus cattle modeled using the characteristics listed in column 6 of Table 1.

For 1997 and 1998, simulated total forage production and utilization agreed more closely with measured values. In 1997, actual hay consumed was 30% greater than that predicted by the model, and in 1996, actual hay consumed was 20% less than that predicted. Predicted and actual pasture consumptions were very similar for these 2 yr (Figure 2). Considering the experimental error that can occur when measuring feed intakes, particularly under grazing, this simulation supports that the model can adequately predict forage production and utilization for a cow–calf production system.

Manure excretions were also verified, but because excretions were not measured in the field trial, another procedure was used. Model-predicted excretions were compared with standard values for beef animals (ASAE, 2003). Simulated annual excretions of manure DM, N, and P for the 15 cow–calf pairs were 37.9 t of DM, 1,805 kg of N, and 227 kg of P, respectively. From the standard values published by ASAE, these animals would produce 36.8 t of DM, 1,470 kg of N, and 398 kg of P. Thus, simulated DM excretion was within 3% of the standard value. Simulated N excretion was 23% greater than the standard value. Because these animals were primarily fed a high-protein pasture diet, a higher N excretion would be expected compared with values primarily developed from confinement animals fed lower-protein diets. The much lower excretion of P is also likely due to feeding differences. In the simulation, P was fed to

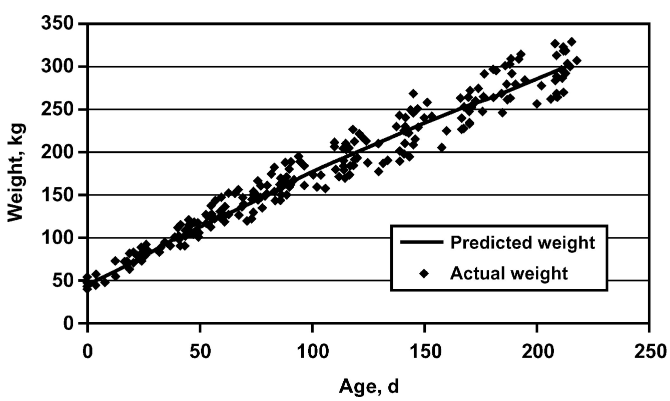

Figure 1. A comparison of model-predicted calf weight to that measured for individual animals on a grazing trial with cow–calf pairs grazing orchard grass and bluegrass near State College, PA (Comerford et al., unpublished results). The root mean square error of the actual weights vs. the model prediction was 15.9 with an r^2 value of 0.96.

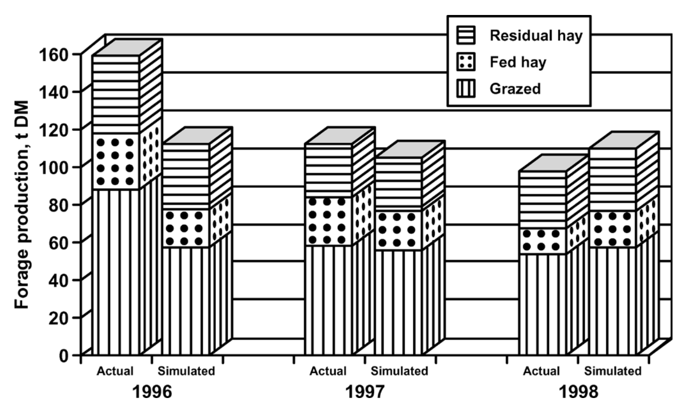

Figure 2. Simulated forage production and utilization for 15 cow–calf pairs on 19.9 ha of cool-season grass pasture compared to that measured in a grazing trial near State College, PA during 1996 to 1998 (Comerford et al., unpublished results). Ninety-five percent confidence intervals for the grazed, fed, and residual forage production measurements were 19.0, 9.4, and 17.8 t of DM, respectively.

Table 4. Average annual feed production, feed use, nutrient balance, production costs, and net return of three representative beef producing farms in central Pennsylvania[a]

Output item	Cow–calf[b]	Finish[c]	Cow–calf to finish[d]
Hay and silage production, t of DM	293	0	194
Corn silage production, t of DM	0	124	108
Corn grain production, t of DM	0	549	64
Grazed forage consumed, t of DM	398	0	322
Forage purchased (sold), t of DM	4	0	0
Corn grain purchased (sold), t of DM	17	(107)	18
Protein and minerals purchased, t of DM	3	38	6
Meat production, kg/ha	437	835	541
N lost by volatilization, kg/ha	51	56	56
N lost by leaching, kg/ha	60	16	49
N lost by denitrification, kg/ha	15	13	13
P accumulation, kg/ha	0	0	0
K accumulation, kg/ha	0	27	0
Feed and pasture production cost, $	34,500	62,800	43,400
Manure handling cost, $	0	4,000	1,800
Animal facility cost, $	1,300	12,600	2,700
Labor cost, $	10,200	8,900	11,700
Net purchased feed cost, $	3,900	(100)	4,800
Animal purchase and maintenance cost, $	9,700	454,500	14,000
Property tax, $	3,300	4,100	3,400
Total production cost, $	62,900	546,800	81,800
Production cost per unit gain, $/kg	1.44	1.46[e]	1.51
Animal sale income, $	79,400	544,600	92,400
Net return to management, $	16,500	–2,200	10,600
Standard deviation in annual net returns, $	6,000	14,600	6,300

[a]All farms used a land base of 100 ha of medium loam soil and were simulated using State College, PA, weather from 1978 to 2002.
[b]135 cows are maintained producing 28 replacement heifers and 101 weaned calves each year.
[c]500 backgrounded cattle are purchased each year to produce 497 finished animals.
[d]100 cows are maintained producing 21 replacement heifers and 76 finished animals each year.
[e]Does not include the cost of purchasing backgrounded cattle

meet current recommended requirements (NRC, 2000). Thus, P intake was essentially that in the forage consumed. The ASAE standard values are based on older studies where higher amounts of mineral P were likely fed.

Beef Production Systems

As a final evaluation and demonstration of the whole-farm model, three full production systems were simulated as farms in central Pennsylvania. These included cow–calf, finish, and cow–calf to finish operations. All three scenarios were simulated for the same 100-ha land base. The soil was a medium loam soil typical of this region. The representative farms were simulated for 25 weather years using State College, PA, weather from 1978 to 2002. The investment in equipment and facilities was relatively low in all scenarios, with corn production operations done by custom hire. Stocker and finish cattle were treated with implants and ionophores. Average annual feed production and utilization, nutrient losses, production costs, and net returns to management for the three systems are compared in Table 4.

For the cow–calf system, the land was used to produce a perennial grass pasture with a long-term average production of 6.4 t of DM/ha. Extra forage in the spring and early summer was harvested as bale silage that was fed during the winter and other periods when sufficient pasture was not available. This forage production supported 135 Angus cows with 28 replacement heifers produced each year. Considering the assumed rates for twins and calf mortality, 101 weaned calves were produced and sold annually at an age of 7 mo. Annual weight sold varied with pasture production, giving an average calf weight of 280 kg. Cull cows were sold at a price of $0.90/kg and calves were sold at $2.30/kg. Equipment owned and operated by the farmer included two tractors, a mower conditioner, hay rake, large round baler, bale wagon, and bale wrapper. Pasture costs included a $20,000 investment in perimeter fence and $9,500 for temporary fence and watering equipment.

For the finish operation, the land was used to produce corn with average annual yields of 13.8 t of DM/ha for silage and 6.6 t of DM/ha for high-moisture grain. This production was used to finish 500 backgrounded Angus cattle each year. Stocker cattle were bought with an average weight of 406 kg at a price of $2.09/kg. Considering a death loss, this produced 497 finished animals at an average weight of 577 kg that were sold at $1.90/kg. Corn production required an annual cost for seed, fertilizer, and chemicals of $220/ha. To decrease equipment costs on this relatively small farm, tillage, planting, and corn harvest operations were custom hired using typical rates for this region.

For the third scenario, calves were born, backgrounded, and finished on the same farm. The land was used to produce 80 ha of perennial grass and 20 ha of corn. Excess pasture grass was harvested as bale silage, and a portion of the corn was harvested as silage for winter-feeding. The remainder of the corn was harvested as high-moisture grain, which was fed to finish cattle. Feeds produced were used to maintain 100 Angus cows. Calves produced each year provided 21 replacement heifers and 75 stocker cattle. Stockers were backgrounded and finished to produce 74 finished animals each year at a weight averaging 577 kg.

A comparison of the three farm systems shows that the finish operation produced the greatest amount of meat, producing approximately twice that of the cow–calf operation (Table 4). Raising calves through finishing produced 24% more meat per unit of land than the cow–calf operation. From an environmental perspective, the major difference was predicted N leaching loss to ground water. Volatile N losses to the atmosphere were high and similar for all scenarios due to high ammonia losses from feedlots and pastures. The pasture-based systems had greater N loss through leaching, which primarily occurred under urine deposits. For all three scenarios, most of the feed was produced on the farm and minimal amounts of mineral P were required, so they were able to maintain a long-term P balance.

Farm profitability varied across the three scenarios. Production costs were lowest for the cow–calf operation due to lower crop production costs, no manure handling, and a low investment in facilities. The overall net return to management was $16,500/yr. Production costs were much higher for the finishing operation due to greater feed production and facility costs, but the major cost was the purchase of backgrounded cattle for finishing. With the prices assumed, this farm was not able to operate at a profit (Table 4). The third scenario provided a profit of $10,600/yr. Production costs were greater than those of the cow–calf operation, but carrying animals through finishing increased income enough to offset much of this increased cost (Table 4).

The intent of this representative farm analysis is to illustrate and further verify the use of the beef herd model in simulating and evaluating whole farm systems. This brief analysis is not meant to make a conclusive comparison of these production options. Complete details on the many assumptions made in representing these farms are also beyond the scope of this paper. Comprehensive analyses are planned where model applications will be documented in more detail. In these planned studies, the whole-farm model will be used to represent actual farms and to evaluate alternative production systems on these farms.

Model Availability

Integration of this beef herd production component with the crop production, harvest, storage, feeding, manure handling, and other components of the farm model provides a useful research and education tool. This IFSM can be used to evaluate the long-term production, environmental impact, and profitability of various alternatives in beef as well as dairy and crop production (Rotz and Coiner, 2003). Production alternatives include many individual and combinations of changes in crop and pasture production, feed harvest and storage, animal feeding and maintenance, and manure handling.

The IFSM is available from the Internet homepage of the Pasture Systems and Watershed Management Research Unit (http://pswmru.arsup.psu.edu). The program operates on computers that use any Microsoft Windows operating system (Microsoft Corp., Redmond, WA). To obtain a copy of the program, including an integrated help system and reference manual (Rotz and Coiner, 2003), the home page can be accessed at the address given, where instructions for downloading and setting up the program are provided.

Implications

Development and incorporation of a beef herd component with the former Dairy Forage System Model has formed the Integrated Farm System Model, a farm-level model for simulating beef, dairy, and crop (no animal) production systems. This integrated model provides a unique research and education tool for evaluating the performance, environmental impact, and economics of beef farm systems over many weather years. The model is available for researchers to evaluate, compare, and develop new production systems that are more environmentally and economically sustainable. The model is also available for classroom, laboratory, and individual use to study the whole-farm effects of management and technology changes.

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