A DETERMINISTIC COMPUTER SIMULATION MODEL
OF LIFE-CYCLE LAMB AND WOOL PRODUCTION1,2

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ABSTRACT

A deterministic mathematical computer model was developed to simulate effects on life-
cycle efficiency of lamb and wool production from genetic improvement of performance
traits under alternative management systems. Genetic input parameters can be varied for
age at puberty, length of anestrus, fertility, precocity of fertility, number born, milk yield,
mortality, growth rate, body fat, and wool growth. Management options include mating
systems, lambing intervals, feeding levels, creep feeding, weaning age, marketing age or
weight, and culling policy. Simulated growth of animals is linear from birth to inflection
point, then slows asymptotically to specified mature empty BW and fat content when
nutrition is not limiting. The ME intake requirement to maintain normal condition is
calculated daily or weekly for maintenance, protein and fat deposition, wool growth,
gestation, and lactation. Simulated feed intake is the minimum of availability, DM physical
limit, or ME physiological limit. Tissue catabolism occurs when intake is below the
requirement for essential functions. Mortality increases when BW is depressed. Equations
developed for calculations of biological functions were validated with published and
unpublished experimental data. Lifetime totals are accumulated for TDN, DM, and protein
intake and for market lamb equivalent output values of empty body or carcass lean and
wool from both lambs and ewes. These measures of efficiency for combinations of genetic,
management, and marketing variables can provide the relative economic weighting of traits
needed to derive optimal criteria for genetic selection among and within breeds under
defined industry production systems.

Key Words: Sheep, Efficiency, Production Economics, Systems, Simulation, Selection
Criteria


Introduction

An animal production system is complex, and a systematic approach is required to
predict effects on production efficiency from changes in potential genetic performance and
in management. Computer simulation is a tool for modeling such effects. Through helpful
collaboration with H. D. Blackburn, the deterministic Texas A&M University sheep model
(TAMU; Blackburn and Cartwright, 1987, Blackburn et al., 1987) was adapted to
facilitate simulation of changes expected in several measures of biological and economic
efficiency of lamb and wool production when genetic potentials for components of perform-
ance were varied under defined production-marketing systems. The ultimate objective was
to estimate the relative economic weightings of traits needed to develop optimal criteria for
genetic selection among and within breeds for

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improved efficiency of lamb and wool production using alternative industry systems. This first paper describes the basic model and presents results from the individual ewe and lamb model to demonstrate the nature of biological functions simulated and to provide a basis for validation.

Materials and Methods

The Texas A&M University model (TAMU) obtained in 1982 was first used to simulate sheep production in northern Kenya, where production environment is harsh and performance level low. All the equations in the original model were tested and modified, when necessary, to generate performance levels conforming to the types of sheep and production environments in North America. Data from sheep experiments at the U. S. Meat Animal Research Center (USMARC), Clay Center, NE, were the major source of information used for modifications. Only those equations that differ from the TAMU model will be presented here. Time periods of 7 d (vs 15 d in the TAMU model) were used for the calculations and collection of information on growth, feed intake and other functions, except for the daily simulations done during the postweaning periods of lambs to closely monitor age at desired market weight.

The genetic potentials that can be varied to simulate breed differences or selection responses are mature empty BW of ewes (WMA), birth weight of single lamb from mature ewe (WO, by changing the percentage of WMA at birth); empty BW at inflection point (SM, by changing the percentage of WMA at birth); fat content in WMA at maturity (FAT), daily fiber growth (WOOL) per unit of surface areas (WT^-6), peak potential daily milk production (MILK) per unit of metabolic body size (WT^-75), fertility (FERT) and percentage of maximum deviation of peak from base fertility at 1 yr of age in optimum season (PREC), length of estrus season (ES), lambing rate at 2 yr of age (LB), and mortalities (MRT) under normal condition for ewes and for single lambs. Management alternatives include mating systems, lambing intervals, feeding levels, creep feeding, weaning ages, marketing weight, or age and culling policy.

General. The TAMU model simulates the potential growth of sheep when nutrition is not limiting according to a curve that is linear from birth to inflection point and then asymptotic to average mature empty body weight (EBW = WMA). The modified standard growth curves begin with WO of single born lambs at 9.5% of WMA of the ewe (Dickerson and Glimp, 1975; Dickerson, 1977), and with 3% fat in WO. Simulated WO are then adjusted for number of fetuses, potential mature weight of fetuses, and current weight of the ewe. The WMA, WO = .095WMA and mature FAT = .34WMA, all are potentially variable genetic parameters. A unit of gain is made up of essential (3% fat and 65% lean) and nonessential gains. When energy and protein intake fluctuate, the animal will gain or lose weight, primarily fat. When energy intake exceeds the requirement for normal growth, the modified model simulates animal storage of fat asymptotically to a maximum 20% above normal EBW (Olthoff and Dickerson, 1989a). Controlling this increase is the physiological limit for feed intake. When protein and(or) energy intake are(is) below normal requirements, available nonessential tissue is mobilized, in descending order of lean for protein, 1/3 ratio of lean/fat for energy, fat for energy, and lean for energy. If intake plus tissue mobilization fail to meet normal requirements, available nutrients are partitioned among various uses according to their assumed priorities. The priority of each function for available ME is visualized as inversely proportional to its elevation from a baseline. Maintenance has highest priority, followed by wool fiber growth, gestation, lactation, and essential growth, as illustrated in the "container" diagram by Blackburn and Cartwright (1987). Nonessential growth begins after all the above requirements are satisfied, and additional body fat stores arise from energy intake above requirements for normal EBW and composition. The model also calculates protein requirements, but simulations may be performed with all protein requirements met for normal growth and function.

Energy Intake Requirements. Calculations of feed energy required for various biological functions are all expressed in terms of ME (Mcal/d), although total inputs are converted to units of TDN.

Maintenance includes basal metabolism, urinary loss, and work. Weight of body lean
tissue (XLN, kg) has replaced BW in the calculation of basal metabolism (MB, Mcal/d) to reflect the closer relationship of metabolic rate to lean tissue than to total BW (Graham, 1967; Olthoff and Dickerson, 1989b). Daily basal metabolism is also influenced by age (AGEP, wk) and by previous period weight change (DEBW, kg): MB = .03653(XLN) + .11267DEBW. Energy spent on daily hours standing (STD) (1.00034 kcal/h)]STD, Graham, 1964) also was added as expenditure for activity, to allow application to variation in foraging. The term NDP is number of days per period. Requirement for growth is calculated from rate of deposition for lean and fat, using energy contents of 9.4 and 5.7 kcal/g and efficiencies of ME use of .78 for fat and .18 for protein deposition, but .44 for protein when intake is milk (Rattray and Joyce, 1976).

The TAMU model requirement for fiber growth is a function of genetic potential, season, and distance from the equator but is expressed per unit of surface area (WM, m²) to make genetic scaling of wool growth nearly independent of body size (Mitchell, 1927). Requirement for gestation is based on composition of conceptus and mammary gland (Rattray et al., 1974) and is the sum of requirements for growth of conceptus and mammary gland and for conceptus maintenance, with efficiencies in converting ME to NE of .18, .425, and .80, respectively. Requirement for lactation is determined by genetic potential, period of lactation, age, and metabolic size of the ewe, and demand by the lambs.

Limits on Feed Intake. Total energy intake of the animal is determined by the smallest of physiological limit (R1), physical limit (R2), or availability (R3) in the TAMU model. Maximum daily rate of energy gain (MXEG) is the amount of energy gain that can be deposited in 1 d toward a maximum 20% above normal EBW at maturity (42% fat in EBW, Olthoff and Dickerson, 1989a): MXEG = .1872 EBW.55(WM/WMA)−10(−4.8316 + 14.858EBW/WMA − .0263(EBW/WMA)²), where WM = expected normal empty weight at any age for a given WMA. MXEG = 0 when EBW/WMA = 1.2, and R1 then includes no energy for weight gain. The original TAMU equation allowed animals to become 50% overweight (mostly fat) before MXEG = 0 and was later changed to 40% over normal weight.

However, when the simulation only deals with normal growth, physiological limit is not used and remains debatable. Calculation on physical limit (R2) was modified to generate more reasonable estimates of gut capacity for pre-weaning lambs (Notter et al., 1984): R2 = 0.0799(WMA/WM)0.075WMA.575e−5.8(1 − DIG²), where DIG is digestibility of dry feed, with maximum of 85%. Physical limit decreases during the last 6 wk of gestation for ewes carrying more than one fetus and increases in the lactating ewe. Catabolism of tissue when intake fails to meet requirement depends on the daily availability of fat and lean from nonessential tissue that can be mobilized.

One of the feeding practices simulated was providing just enough energy to meet requirement for normal growth and condition, by adjusting the digestibility of the feed to the level where gut capacity would allow the animal to remain in normal condition during each stage of the reproductive cycle. Other feeding strategies can also be simulated, including restricted feeding of ewes during open nonlactating periods and early pregnancy, or the feeding of a specified ration. Creep feeding of lambs is optional.

Mortality. Mortality of ewes and lambs is calculated from a standard mortality for animals under normal condition, and adjusted for the deviation of BW from normal as affected by litter size or nutrition. Standard mortality of ewes is an input parameter determined by the genetic level and type of environment simulated. Standard mortality of lambs is that for lambs born and reared as singles. Standard mortality for normal single lambs at birth (MRTB) is calculated as a linear function of mortality at weaning (MRTW): e.g., MRTB = .026 + .161 MRTW, as estimated from data collected at USMARC, but can vary with breed and management system (da Gama, 1988). Standard mortality of a normal single lamb per 7-d period (DMRT) from birth to weaning is then calculated as a constant fraction (QFRAC = .334) of the remaining mortality to weaning (MRTW − MRT) at that time (Tess et al., 1983). Standard rate of postweaning mortality (DMRT) is the same as during the last week before weaning. Effects of litter size or nutrition on mortality are simulated through their effects on BW.

Lifetime Production. To simulate the lifetime production of a flock, functions related to reproductive performance are included in the
program. Fertility (FERT) of ewes is determined by genetic potential for peak of breeding season at 2 yr of age and adjusted for precocity of fertility, age, season, and deviations from normal BW (EBW – WM). Average number of lambs born (LB) is a quadratic function of mean genetic lambing rate at 2 yr and ewe age, adjusted for condition of the ewe at breeding. Distributions of birth types are quadratic functions of number born. Derivations and descriptions of these traits and functions will be discussed in companion papers, in which results from the flock model are presented (Wang and Dickerson, 1991a,b).

Output Examples. An individual ewe form of the model was first examined to test the reasonableness of the functions simulated. The ewe started with first breeding at 31 wk of age to lamb at 1 yr and continued through five annual lambings. Three patterns of lambing rates were simulated: five successive single lambings, two of singles followed by three of twins, and two of twins followed by three of triplets. Both ewe and lamb(s) were fed to energy and protein requirement for maintaining normal body condition. Lambs were weaned at 11 wk of age and marketed at 30 wk of age. No ewe mortality or culling was simulated, and one ewe lamb was retained to 31 wk of age as a replacement. A second feeding regimen was simulated to show weight fluctuation from restricting feed energy intake to 90% of the ewe maintenance requirement from 4 wk after weaning until 4 wk before breeding and again during first 14 wk of gestation. Genetic parameters that were constant for the simulation were WMA = 60 kg, WO = .95 WMA, and FAT = .34 WMA. Inflection point on growth curve (SM) was reached in 165 d with SM = .5 WMA. Daily wool growth (WOOL) was 8.1 g/d for WMA = 60 kg.

Results

A growth curve for a 60-kg (WMA) mature sheep with genetic potential for 34% fat in EBW at maturity when fed to requirements for normal body condition is illustrated in Figure 1. Empty body weight change is linear from birth to puberty (SM) then increases asymptotically toward 60 kg. The EBW is made up of FAT and LEAN (EBW – FAT). The amount of FAT starts at 3% of WO and in the present application approaches 34% of EBW at maturity for ewes fed to requirement (Olthoff and Dickerson, 1989a) to maintain normal condition. Live BW of ewes during gestation and lactation fluctuates around the normal growth curve according to the stage of reproduction and ME intake.

Ewe Performance. The pattern of live BW change from breeding to breeding is illustrated in Figure 2 for nearly mature third-parity ewes.

![Figure 1](image-url)  
Figure 1. Normal growth curve for ewes with genetic potential of 60 kg mature empty body weight of 34% fat when all nutrient requirements are supplied. SM = inflection point corresponding to sexual maturity.
at three levels of lambing rate. Weight gain of pregnant ewes becomes more rapid after the first trimester. After parturition, ewes carrying more than one fetus were slightly heavier due to more growth in mammary gland when feeding to requirement. Weight loss at parturition followed by lactation brings ewe weights of all three types to the same level at weaning, only when ewes are fed to full ME requirement. Some weight gain takes place after weaning until next breeding, more in younger than in older ewes.

Because ewes are fed to maintain normal condition, weight changes are reflected in the

Figure 2. Live weights during third parity for ewes of potential 60 kg mature empty body weight, at three lambing rates.

Figure 3. Feed energy requirement during third parity for ewes with potential for 60 kg mature empty body weight containing 34% fat, at three lambing rates.
Figure 4. Required digestibility of dry matter intake during third parity for ewes with potential 60 kg mature empty body weight containing 34% fat, at three lambing rates.

energy requirement at different stages of reproduction (Figure 3). Energy requirement during ages 149 to 156 wk in late gestation for third-parity ewes carrying twins and triplets is 18 and 27% higher than for ewes with a single fetus. With the same peak genetic milk potential (2.7 kg/d), ewes nursing two and three lambs quickly reach their maximum milk level and thus the upper limit of energy requirement. Energy requirement for ewes nursing one lamb increases as the lamb demands more milk and only reaches the limit in late lactation. After weaning, energy requirement of all ewe types returns to the same

Figure 5. Required crude protein intake during third parity for ewes of potential 60 kg mature empty body weight containing 34% fat, at three lambing rates.
level. When energy intake requirement increases, the required digestibility (DIG) and level of CP in the feedstuff also must increase so that gut capacity can allow adequate ME intake for normal growth and function (Figures 4 and 5). As crowding reduces gut capacity during late gestation, required DIG and CP rise sharply for ewes carrying two or more fetuses. As gut capacity increases during lactation, the required DIG and CP levels are lower than during late gestation, even though the energy requirement is higher. The genetic potential for milk production (2.7 kg/d) sets an upper limit of DIG and CP required for ewes nursing more than one lamb.

Lamb Performance. Empty body weight change from birth to marketing at 30 wk of age is illustrated in Figure 6. Triplet lambs weigh 62% and twins 78% of single lambs at birth. When fed to full requirement for attaining normal weight, which includes compensatory growth, weight of multiple-born lambs approached that for singles by 30 wk of age. Less requirement for maintenance but more for growth makes energy requirement for the smaller triplet and twin lambs higher than for singles until they reach normal weight, by 5 and 3% at weaning and about 1% at 30 wk. As shown in Table 1, growing single lambs require 73% DIG and 10.5% CP for normal growth at 12 wk and 70% and 8.1% at 30 wk, and the levels are only slightly higher for twins and triplets.

Milk Production. Potential milk production of the ewe is determined by her genetic potential, mature EBW (WMA), age, and number of lambs nursed. Younger ewes express less of their mature potential and do
not maintain level of production as well as older ewes (i.e., poorer persistency). Genetic potential is expressed as milk (kg/d) for a 60-kg mature ewe at peak of lactation (MILK) with maximum stimulus from her lambs. Table 2 illustrates the potential level of daily milk production (kg/ewe) by parity and week of lactation for ewes nursing one lamb and the lamb’s potential milk intake. Amount of milk produced by the ewe is determined by the smaller of her own potential and the intake limit of the lamb(s). As illustrated in Figure 7, milk production of a 60-kg WMA ewe nursing third-parity triplets shows the same flat pattern for low (1.9 kg), medium (2.7 kg), and high (3.9 kg) genetic daily milk levels because the demand of triplets exceeds all three potential levels and negative slope of potential level is nearly flat from 2 through 11 wk. Ewes of medium milk potential nursing one lamb increase milk production with demand of the lamb through the first 6 wk of lactation and then level off at the ewes’ potential for one lamb. Ewes of medium milk potential nursing two lambs could produce enough milk to meet the demand of lambs during the first 3 wk, but thereafter milk production again was limited by the potential of the ewe. The level of milk potential production reported by Snowder and Glimp (1991) corresponds roughly to the high potential level in the model. The steeper decline reported in daily production after 4 wk

**Figure 7.** Milk production of third-parity ewes of 60 kg potential mature empty body weight for low (L), medium (M), and high (H) genetic milking levels, nursing one, two, or three lambs.
presumably was associated with free access to high-protein creep feed. Restricted Feeding. In practice, ewes often experience periods of restricted feeding due to seasonable availability of forage or management strategy. Restricted feeding was simulated during early gestation (first 14 wk) and from 4 wk after weaning until flushing for next breeding (12 wk). Energy intake was restricted by providing the ewes 90% of the maintenance

Figure 8. Changes in fat and empty body weight for single lambings over five parities of ewes (A) fed ME requirements to maintain normal body condition and (R) fed only 90% of maintenance requirement from 4 wk after weaning until flushing (12 wk) and during the first 14 wk of gestation, beginning after the first-parity lamb is weaned. (For genetic potential of 60 kg empty body weight and 34% body fat at maturity).

Figure 9. Required digestibility (DIG) and dry matter (DM) intake of ad libitum (A) and restricted (R) fed ewes over 5 parities at lambing rate of one (For potential 60 kg empty body weight and 34% fat at maturity).
requirement estimated during the restricted periods. Ewes were not restricted until 4 wk after they weaned their first lambs. As illustrated in Figure 8, ewes lose weight during postweaning periods of restricted feeding and regain some weight during flushing. Weight loss occurs again after restriction begins during early gestation until ewes are back on full feeding during late gestation, lactation, and postweaning recovery periods. The same cyclic pattern continues for the number of parities simulated along the normal growth curve from feeding to full requirement for both EBW and FAT. Restricted ewes are still growing toward mature size and fat content, but at a slower rate.

As shown in Figure 9, total dry matter intake (DM) was almost the same for ewes fed to requirement and those restricted, because the two groups have similar gut capacity. Digestibility of feed was lowered during restricted feeding periods to accomplish the reduced energy intake. To compensate for weight lost during restriction, the ewe's normal energy requirement after restriction includes the extra amount required to regain normal weight, and thus DIG must be higher than for unrestricted ewes.

The energy intake requirements to maintain normal body condition as simulated by the model were compared with those recommended by ARC (1980), NRC (1975), and Rattray (1986) in Table 3. Because of differences in growth rate and condition of the animals and in production environment, estimates of requirements are expected to differ among sources. In general, Rattray's estimates were higher and ARC's lower than NRC's recommendations. Requirements generated by the model for ewe maintenance were similar to those of NRC (1975) and Olthoff et al. (1989) but higher than those of ARC (1980), possibly because of feeding to maintain normal weight and condition. Total requirements simulated for nonpregnant, nonlactating ewes also include requirements for wool growth. However, the corresponding requirements modeled are within the range of recommended energy intake for reproducing, lactating ewes and growing lambs. Differences from literature cited also may be attributed to variation in milk potential and in period of lactation. One advantage of simulation is the ability to calculate requirements for different stages in production according to the specific conditions of interest.

### Table 3. Daily Energy Intake Requirements (Mcal ME) To Maintain Normal Body Condition at Different Stages of Life As Calculated by the Model and As Recommended by ARC, NRC, and Rattray for Sheep (60 kg Mature Empty Body Weight)

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<tbody>
<tr>
<td>Maintenance</td>
<td>2.42</td>
<td>2.00</td>
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<tr>
<td>Nonpregnant, mature ewe$^a$</td>
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<td>—</td>
<td>2.78</td>
<td>2.82</td>
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<tr>
<td>Gestation</td>
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<tr>
<td>Early and mid</td>
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<tr>
<td>Singles</td>
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<td>2.78</td>
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<tr>
<td>Twins</td>
<td>3.20</td>
<td>2.43</td>
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<td>Late</td>
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<tr>
<td>Singles</td>
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<tr>
<td>Lactation</td>
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<td>First 6 to 8 wk</td>
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<tr>
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<td>4.40</td>
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<td>Lambs at weights</td>
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<td>1.35</td>
<td>1.24</td>
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<td>—</td>
<td>4.20</td>
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$^a$Energy requirement for open ewes includes maintenance plus growth of grease wool at rate of 13.5 g/d.
Discussion

The basic biological model of sheep production described here is designed to simulate ewe and lamb performance and energy intake requirements to maintain normal BW and condition during phases of the life cycle for variable genetic levels of mature size, lambing rate, body composition, wool growth, and milk production. It also can simulate performance and intake under patterns of energy intake restriction. The simulation results presented illustrate the nature and validity of the model and its degree of agreement with recommended feeding standards.

Although not illustrated here, the model also can accumulate feed energy and cost inputs and lamb, wool, and cull ewe outputs over the life cycle and compute effects from varying weaning age, creep feeding, age at puberty, and age or weight at marketing. Extension to a flock model (Wang and Dickerson, 1991a) also permits evaluating effects of genetic levels of fertility, mortality, precocity of fertility, and of such management options as culling policies and crossfostering. In addition, effects of different lambing intervals on production efficiency also were simulated (Wang and Dickerson, 1991b).

With further branching into subpopulations, the model can evaluate different breeding systems, such as straight breeding, two- or three-way specific crosses, two- or three-way rotation crossing, composites, and terminal-sire systems. Costs and prices can also be incorporated to investigate economic considerations. Ultimately, results can be used to estimate the relative economic weightings of traits for developing optimum genetic selection programs for improved efficiency of lamb and wool production among and within breeds under defined industry systems.

Implications

Effective selection for more efficient production of market lamb and wool within breeds, or among alternative breeds or cross-breeding systems, requires estimation of the relative effect of genetic changes in such traits as growth rate, body composition, wool growth, fertility, length of anestrus, litter size, milk production, and lamb mortality on production costs per unit of output value, under representative management systems and cost/price structures. The mathematical computer model of sheep production described here can use prior knowledge from research to estimate the relative importance of these alternative genetic changes. These relative values can be used with estimates of heritability and genetic associations among traits to develop more effective sheep breeding programs.

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