Development and application of a crossbreeding simulation model for goat production systems in tropical regions

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ABSTRACT: A deterministic simulation model was developed to estimate biological production efficiency and to evaluate goat crossbreeding systems under tropical conditions. The model involves 5 production systems: pure indigenous, first filial generations (F1), backcross (BC), composite breeds of F1 (CMPF1), and BC (CMPBC). The model first simulates growth, reproduction, lactation, and energy intakes of a doe and a kid on a 1-d time step at the individual level and thereafter the outputs are integrated into the herd dynamics program. The ability of the model to simulate individual performances was tested under a base situation. The simulation results represented daily BW changes, ME requirements, and milk yield and the estimates were within the range of published data. Two conventional goat production scenarios (an intensive milk production scenario and an integrated goat and oil palm production scenario) in Malaysia were examined. The simulation results of the intensive milk production scenario showed the greater production efficiency of the CMPBC and CMPF1 systems and decreased production efficiency of the F1 and BC systems. The results of the integrated goat and oil palm production scenario showed that the production efficiency and stocking rate were greater for the indigenous goats than for the crossbreeding systems.

Key words: crossbreeding, goat, production efficiency, simulation model, the tropics

INTRODUCTION

Over the last 20 yr, goats have shown the largest increase in numbers among all domestic animals used as livestock (Dubeuf and Boyazoglu, 2009). Goats are largely found in developing regions all over the world, and make significant contributions to the food and economic security of these areas (Sahlu and Goetsch, 2005). However, the supplies of goat products (meat and milk) are inadequate to meet the growing demand in recent years and projected future human requirements (Devendra, 2007). To increase the level of goat production, numerous crossbreeding programs have been carried out for several decades (Shrestha and Fahmy, 2007). However, in developing countries in the tropics, crossbreeding programs in goats have not always succeeded, because often the resultant crossbred goats are not adapted to the environment (Devendra, 2007).

Simulation models can provide a logical understanding and predictions of outcomes of the production systems including genetic, managerial or environmental variables under different sets of conditions. Several simulation models with different purposes have been described for various livestock species. For goats, simulation models have been developed to assess the efficiency of goat production (Bosman et al., 1997), to evaluate the biological and economic potentials of characterized smallholder production systems (Bett et al., 2007) and to estimate the effect of the culling age of does on the productive efficiency (Oishi et al., 2008). However, simulation models to evaluate goat crossbreeding systems for goat production have seldom been reported (Bett et al., 2011).

The objectives of this paper were to develop a goat production model and to estimate the production efficiency (PE) in different crossbreeding systems. Furthermore, the model was applied to evaluate 2 scenarios for production systems under tropical conditions: 1) an intensive milk production system and 2) an integrated goat and oil palm production system in Malaysia.

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MATERIALS AND METHODS

Animal Care and Use Committee approval was not obtained for this study because no animals were used.

Model Overview

A deterministic model is described as a model that makes definite predictions for outputs without any associated probability distribution, whereas a stochastic model contains some probability distribution and complexity (Thornley and France, 2007). Deterministic models have been widely used to estimate biological efficiency of livestock production systems (Long et al., 1975; Blackburn and Cartwright, 1987). In this study, a deterministic goat production model, programmed in Fortran 90, was developed for the evaluation of crossbreeding systems appropriate to developing countries in the tropics.

Five goat production systems were considered in this study: pure indigenous (PI), first filial generation (F1) composite (CMPF1), backcross (BC) composite (CMPCBC), F1, and BC production systems; PI (CMP) system contains single PI (CMP) herd, F1 system contains PI + F1 herds, and BC system contains PI + F1 + BC herds.

This model consists of individual modules for doe and for kid, and a herd dynamics program. The model first simulates growth, reproduction, lactation, and energy intakes of a doe and a kid on a 1-d time step at the individual level, and thereafter the outputs are integrated into the herd dynamics program. At the individual level, survivability, litter size, growth, milk production, and nutrient requirements are expressed by equations and calculated in each module. At the herd level, the 5 crossbreeding systems are defined to estimate total herd outputs (meat and milk in kilograms) and ME intake (MJ) of a whole life cycle. The total biological PE of each system was finally calculated on a single doe basis.

Individual Level

At the individual level, the goat biological model described by Oishi et al. (2008) was used (Appendix A). The estimation of ME requirements for each production stage is based on AFRC (1998). Daily biological changes of survivability, litter size, growth, milk production, and nutrient requirements are expressed by equations and calculated in each module. The daily biological changes for a doe and a kid are calculated separately in each module by crossbred genotype. The module-doe concerns survivability, growth, conception rate, pregnancy, delivery rate, litter size, milk production, and ME intake of each reproduction stage. The
module-kid includes survivability, growth, consumption of doe milk, and ME intake. The user-defined input variables are production (growth, lactation, and pregnancy), adaptability (pre- and postweaning mortality), management, and nutrition variables (Table 1). The model can be easily adapted to other crossbreeding schemes and production environments by changing the input variables.

Litter Size and Reproductive Cycle. According to Shelton (1978), reproductive performances of goats are more important than those of other domestic ruminant species because they undoubtedly have the largest litter size among domestic ruminant species. Enhancement of the reproductive performance, such as litter size traits, through crossbreeding has been expected due to low heritability of the reproductive traits. Tsukahara et al. (2008b) reported significant effects of parity and crossbreeding genotype on litter size. The number of kids produced by a doe by parity \( \text{nkid}_x(\text{par}) \) is calculated as

\[
\text{nkid}_x(\text{par}) = \text{surv}_{x,\text{doe}}(t_{\text{part}}(t)) \times LS_x(1) \times \text{coef}(\text{par}) \times (\text{concr}_x \times \text{delr}_x)^{\text{par}},
\]

where \( x \) is genotype, \( \text{par} \) is the number of parities, \( \text{surv} \) is the survival rate of the doe at kidding, \( t_{\text{part}}(t) \) is the age at parturition (see Eq. A9), \( LS_x(1) \) is the mean litter size at the first parity \([= (1)]\) of genotype \( x \), \( \text{coef} \) is the coefficient of the parity, \( \text{concr}_x \) is conception rate of genotype \( x \), and \( \text{delr}_x \) is delivery rate of genotype \( x \). To include the effect of parity on litter size, the procedure using probability reported by Oishi et al. (2008) was applied in this study. Table 2 shows the adjusted coefficients \( \text{coef}(\text{par}) \) representing the effect of parity on litter size.

<table>
<thead>
<tr>
<th>Variable</th>
<th>PI</th>
<th>F1</th>
<th>BC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production variable</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Growth, kg</td>
<td>28.80</td>
<td>32.20</td>
<td>34.20</td>
</tr>
<tr>
<td>Mature weight (female; MW)</td>
<td>1.72</td>
<td>2.33</td>
<td>2.60</td>
</tr>
<tr>
<td>Birth weight (BWT)</td>
<td>7.23</td>
<td>9.06</td>
<td>11.39</td>
</tr>
<tr>
<td>Lactation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total milk yield at first parity ( TMY, ) kg</td>
<td>79.7</td>
<td>133.1</td>
<td>159.8</td>
</tr>
<tr>
<td>Milk fat content (mfat), %</td>
<td>4.61</td>
<td>4.32</td>
<td>4.17</td>
</tr>
<tr>
<td>Lactation length ( t_{lact} ), d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1</td>
<td>120</td>
<td>180</td>
<td>210</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td><strong>Pregnancy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conception rate ( \text{concr} ), %</td>
<td>90.0</td>
<td>74.0</td>
<td>74.0</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>90.0</td>
<td>90.0</td>
<td>90.0</td>
</tr>
<tr>
<td>Delivery rate ( \text{delr} ), %</td>
<td>87.0</td>
<td>87.0</td>
<td>87.0</td>
</tr>
<tr>
<td>Average litter size at the first parity ( \text{LS}(1) ), n</td>
<td>1.71</td>
<td>1.45</td>
<td>1.56</td>
</tr>
<tr>
<td>Sex ratio of litters</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Gestation period ( t_{preg} ), d</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td><strong>Adaptability/survivability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preweaning mortality ( \text{wmort} ), %</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Yearly postweaning mortality ( \text{mort} ), %</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Management variable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weaning age ( t_{\text{wean}} ), d</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Culling age of kids ( t_{\text{cull}} ), d</td>
<td>270</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>Age at first mating ( t_{\text{mtfst}} ), d</td>
<td>270</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>Length of reproduction cycle ( t_{\text{cl}} ), d</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Maximum parity ( \text{parmax} ), n</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

\(^1\text{PI = pure indigenous; F1 = first filial generation; BC = backcross.}\)
\(^2\text{Refereed and calculated from Tsukahara et al. (2008a,b) and the MW of males is assumed to be 20% heavier than females.}\)
\(^3\text{Estimated using data by Mukherjee et al. (1985).}\)
\(^4\text{Scenario 1 = milk production scenario under intensive management system (zero grazing); scenario 2 = meat production scenario under tree crops (grazing).}\)
\(^5\text{Adapted from Tsukahara et al. (2008b).}\)
Table 2. Coefficients representing the effect of parity on litter size

<table>
<thead>
<tr>
<th>Parity</th>
<th>Coefficient $^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00000</td>
</tr>
<tr>
<td>2</td>
<td>1.22229</td>
</tr>
<tr>
<td>3</td>
<td>1.29372</td>
</tr>
<tr>
<td>4</td>
<td>1.33190</td>
</tr>
<tr>
<td>5</td>
<td>1.24200</td>
</tr>
<tr>
<td>6</td>
<td>1.22968</td>
</tr>
<tr>
<td>7</td>
<td>1.22968</td>
</tr>
<tr>
<td>8</td>
<td>1.22968</td>
</tr>
</tbody>
</table>

$^1$Calculated using probability of goat litter size by Oishi et al. (2008).

In the present model, it is assumed that does that failed to conceive are culled at the end of the reproductive cycle. The mortality of the fetus occurs at kidding, and the mortality rate of the fetus is regarded as representing the reproductive failure of the does and expressed as the failure of delivery. The young female replacements that failed to conceive at the first mating are assumed to be culled immediately $(1 - conc)$, and those that fail to deliver are culled at kidding $(1 - delr)$. If the breeding does fail to conceive and deliver after 1 reproduction cycle, then they are assumed to be culled at the end of the lactating period of the reproduction cycle $(1 - conc \times delr)$. The other does are culled when their kids are weaned at the maximum parity.

**Growth.** Postweaning BW changes of all goats are estimated using the von Bertalanffy growth function (von Bertalanffy, 1957). The von Bertalanffy function is adopted in the model according to Tsukahara et al. (2008a), who reported that the function had high goodness of fit (coefficients of determination, $R^2 > 0.91$) to the longitudinal BW-age data taken from a crossbreeding program including indigenous and exotic goats in Malaysia. On the other hand, preweaning daily gains are assumed to be linear. Details of the expressions are shown in Appendix A. The birth, weaning, and mature BW by genotype and weaning age are user-defined variables.

**Milk Production.** Previous studies reported that lactation length was significantly affected by breed (Devendra and Burns, 1983; Montaldo et al., 1995) and management regimen (Gall, 1981). In this model, the values of lactation length are user-defined variables and thought to be set by the genotype and the production scenario. The daily milk yield of a doe is estimated based on the威廉’s lactation curve (Williams, 1993). The parameters of $B$ and $C$ for primiparous does by Oishi et al. (2008) are used and the parameter $A$ is estimated from the total milk yield by genotype given by users. Kennedy et al. (1981) indicated the need to consider the effect of parity for dairy goat lactation. The effect of parity on milk yield is incorporated using Wood’s function (Wood, 1967), as reported by Oishi et al. (2008; see Appendix A).

**ME Intake.** The daily ME intake of an animal is expressed as the sum of the maintenance $(\text{ME}_m)$, growth $(\text{ME}_g)$, pregnancy $(\text{ME}_p)$, and lactation $(\text{ME}_l)$ ME requirements. The estimation was based on the equations by AFRC (1998). Because the energy intake is necessary to estimate PE, the intake is obtained from nutritional requirements and is assumed to be sufficient to meet all energy requirements in this study. This requires the assumption of an unlimited food supply (Tess et al., 1983; that is, it is assumed that animals are not affected by food shortage for the entire period). The ME$_p$ are based on the energy content of the fetus and estimated using the equation by Bosman et al. (1997).

The AFRC (1993) recommended the use of metabolizability ($q$) of feeds as the basis for calculating the efficiencies of ME utilization, to achieve a more precise performance prediction. Therefore, the model involves 3 kinds of $q$ according to different feed resources: roughage ($q_r$), concentrate ($q_c$), and starter feed or dietary supplementation ($q_{spl}$) of preweaning kids (Table 3).

The details of the ME requirement and energy intake for preweaning kids are represented in Appendix A.

**Herd-Level Crossbreeding System**

The calculated individual biological performances of a doe for her whole life and of kids from birth to the age of culling or replacement are integrated by parity in the herd dynamics program according to the production system. Table 4 describes the herd compositions included in each production system, gene of sire used in the herd, genotypes of dam, destination of progeny, and replacement rate of females. Although the number of does decreases due to the change in survival rate and culling between each reproduction, the total number of does in a herd is compensated for by young female replacements at the beginning of each reproduction cycle, and hence, the size of each production system is kept in a steady state. This model functions on a single doe basis. If a producer has large herd size, he can calculate the outputs by multiplying the results according to the number of does. The use of a steady state herd model is a convenient means to compare standard conditions of livestock productivity estimates (Upton, 1989). Details of the expressions for the replacement rate, production outputs, and ME intakes are shown in Appendix B.1.

In the herd dynamics, the outputs and ME requirements calculated in the doe module and in the kid module are combined by parity. For example, accumulated ME requirements (in MJ) of a kid in the kid module are multiplied by the number of kids produced by its doe by parity $[nkid_{par}]$, see Eq. 1, in the herd dynamics, as follows:

$$TKidme_{x,m+f} = \sum_{i=1}^{parmax} nkid_{i} \times 0.5 \times [kidme_{x,m}(i) + kidme_{x,f}(i)]$$

[2]
where $T_{kidmex,m+f}$ is the total ME intake, $x$ is the genotype, $m+f$ is the mean of male and female kids, $parmax$ is the maximum parity, $kidme$ is the ME requirement of an individual kid in parity $i$, $m$ is a male kid, and $f$ is a female kid. Non-replacement female kids ($1-rx$) and all male kids produced are assumed to be sold at the age of 270 d. The daily ME requirement of a doe is accumulated at the individual level and divided by each parity (see Appendix B-1). In the herd dynamics, total ME intakes (in MJ) of culled does are calculated as

$$T_{cullme_x} = \sum_{i=0}^{parmax} cullme_x(i). \quad [3]$$

where $T_{cullme_x}$ is the total ME intake of culled does and $cullme_x$ is the accumulated ME requirements of culled does by parity (see Appendix B-1). The other equations used to calculate the total number of kids for sale, the sale BW of kids, the total culled BW of does, and the milk production for sale are presented in Table 3.

**Table 3. Description of the nutritional variables and default values used in the model**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolizability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total diet ($q_t$)</td>
<td>0.45</td>
<td>0.38</td>
</tr>
<tr>
<td>Roughage ($q_r$)</td>
<td>0.70</td>
<td>NA²</td>
</tr>
<tr>
<td>Concentrate ($q_c$)</td>
<td>0.60</td>
<td>0.38</td>
</tr>
<tr>
<td>Supplementation for kids ($q_{spl}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjustment of activity³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal movement ($hrz$), m/d</td>
<td>500</td>
<td>5,000</td>
</tr>
<tr>
<td>Vertical movement ($vert$), m/d</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Times of position change ($chg$)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Additional energy cost for</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal movement ($E_{hrz}$), J/kg per m</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Vertical movement ($E_{vert}$), J/kg per m</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Standing ($E_{stn}$), KJ/kg per d</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>One position change ($E_{chg}$), KJ/kg per n</td>
<td>0.26</td>
<td>0.26</td>
</tr>
</tbody>
</table>

¹Scenario 1 = milk production scenario under intensive management system (zero grazing); scenario 2 = meat production scenario under tree crops (grazing).
²NA = not applicable.
³Derived from AFRC (1998).

**Table 4. Description of crossbreeding production systems involved in the model**

<table>
<thead>
<tr>
<th>Production system¹</th>
<th>Sire</th>
<th>Dam</th>
<th>Male</th>
<th>Female²</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI Doe and kid PI</td>
<td>PI</td>
<td>Market</td>
<td>$r_{PI}$</td>
<td>Replacement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1 - r_{PI}$</td>
<td>Market</td>
</tr>
<tr>
<td>F1 Doe and kid Exotic PI</td>
<td>PI</td>
<td>Market</td>
<td>$r_{PI}$</td>
<td>Replacement for PI production</td>
</tr>
<tr>
<td>Kid PI</td>
<td>Exotic</td>
<td>Market</td>
<td>$1 - r_{PI}$</td>
<td>F1 production</td>
</tr>
<tr>
<td>BC Grand-doe (first generation) PI</td>
<td>PI</td>
<td>Market</td>
<td>$r_{PI}$</td>
<td>Replacement for PI production</td>
</tr>
<tr>
<td>Doe (second generation) Exotic</td>
<td>PI</td>
<td>Market</td>
<td>$1 - r_{PI}$</td>
<td>F1 production</td>
</tr>
<tr>
<td>Kid Exotic</td>
<td>F1</td>
<td>Market</td>
<td>Market</td>
<td></td>
</tr>
<tr>
<td>CMPF₁ Doe and kid CMPF₁</td>
<td>CMPF₁</td>
<td>Market</td>
<td>$r_{CMPF₁}$</td>
<td>Replacement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1 - r_{CMPF₁}$</td>
<td>Market</td>
</tr>
<tr>
<td>CMPBC Doe and kid CMPBC</td>
<td>CMPBC</td>
<td>Market</td>
<td>$r_{CMPBC}$</td>
<td>Replacement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1 - r_{CMPBC}$</td>
<td>Market</td>
</tr>
</tbody>
</table>

¹PI = pure indigenous; BC = backcross; F1 = first filial generation; CMPF₁ = F1 composite; CMPBC = BC composite breeds.
²$r =$ replacement rate.
Model Evaluation

Appropriate evaluation of a simulation model is a very important process. Various techniques are used in model validation, often in combination, but there is no uniform procedure to this end (Bosman et al., 1997). This goat production model was evaluated following 2 approaches. First, the model simulated under a base situation and the obtained outputs were evaluated by simulating the performance representative of indigenous goats under tropical conditions at several points in the life cycle. This approach can be used to examine not only the final summation of inputs and outputs, but also the behavior of the model (Tess et al., 1983). Second, the simulated outputs were compared with other published values that were not used to construct the model.

Table 1 presents user-assigned input variables of production, adaptability, and management for each genotype. Most of the variables were adopted from the literature (Mukherjee et al., 1985; Tsukahara et al., 2008a,b). Common values of the age at first mating, culling age of kids, maximum parity, and sex ratio of litters were set as the values typically cited for goat production in the tropics. Reproduction cycle was set for 240 d regardless of the season in this model, following reported average postpartum intervals (between 89.4 and 106.3 d) and gestation lengths (between 143 to 153 d) of local goats in Southeast Asia (Devendra and Burns, 1983). The default values of litter size, birth weights, and mature BW by crossbred goats were based on the reported mean values. The weaning weights were estimated from the Bertalanffy growth function for crossbred goats given by Tsukahara et al. (2008a).

It was necessary to define the total milk yield for each genotype to estimate the daily milk yield using William’s lactation curve in this study. In this application, the primiparous total milk yields of PI and F1 does under tropical conditions were estimated using the average daily milk yield data of the primiparous does collected in a crossbreeding project in Malaysia by Mukherjee et al. (1985). The data were initially fitted to Wood’s lactation curve \( y(t) = a t^b \exp(-ct) \) (Wood, 1967) using the PROC NLIN (SAS Inst. Inc., Cary, NC). The \( a, b, \) and \( c \) indicate lactation parameters; \( t \) is the lactation period in weeks; and \( y \) is milk yield at \( t \). The estimated parameters \( a, b, \) and \( c \) were 544.51, 0.0816, and 0.0639 for indigenous does and 765.30, 0.1959, and 0.0759 for F1 does, respectively. A lactation length of 240 d was assumed in this calculation (see Appendix A). The estimate of total milk yield for BC does was calculated as an additive exotic breed effect of 75% over that for indigenous breeds.

Application of the Model to Goat Production in Malaysia

The 2 conventional goat production scenarios in Malaysia were examined using the model in this study as an example. Tables 1 and 3 show the default variables assumed by scenario.

Milk Production Scenario Under an Intensive Management System. An intensive milk production scenario in Malaysia was assumed in this scenario. The 5 crossbreeding systems were included to compare the milk PE and the total PE. The default values of the conception rate for crossbreeding herds (F1 and BC) using AI were assumed to be 74% (Sohnrey and Holtz, 2005), and those of indigenous, CMP\(_{F1}\), and CMP\(_{BC}\) herds with natural matings were assumed to be 90% in this scenario. The default values of the delivery rate in the scenario were set at 87%, which was estimated from the average abortion rate of 8.8% (Devendra and Burns, 1983) and the overall incidence of stillbirths of 4.2% (Mellado et al., 2006). The mortality of preweaning kids was assumed to be 6.0% under an intensive dairy goat production system (Guimaraes et al., 2009).

The management regimen assumed in this scenario was that the kids were weaned at age 90 d and fed by a cut-and-carry system. The nutrition was provided with improved forage for the entire period and concentrated feed was provided for lactating does. The amounts of concentrated feed used were determined as 10, 20, and 30% of total DMI and simulated to define the production efficiencies by production system. The ME intakes from concentrate (ME\(_{con}\)) and roughage (ME\(_{rough}\)) were estimated from the metabolizability of the total diet, \( q_r \), and \( q_c \) (see Appendix C). Kids were provided supplement or starter feed \( (q_{sup} = 0.6) \) when the nutrition from dam milk was not sufficient for their requirements before weaning (Appendix A). Weaning was assumed to occur at an age of 90 d, regardless of BW.

Meat Production Scenario Under an Integrated Goat and Oil Palm Production System. In this scenario, the efficiencies of integrated goat-oil palm production systems in Malaysia were compared. Malaysia has about 4 million hectares of available land beneath oil palm canopy and there is increased interest by the public sector in establishing integrated farming systems for producing tree crops and ruminants (Devendra, 2007). This interest has grown along with public awareness of the benefits of such systems, which include the production of milk and meat for the agricultural workers, the savings on weeding costs, and the production of dung and urine to enhance soil fertility and crop growth (Devendra, 2007). To manage the ground vegetation effectively, systematic but flexible grazing management is required to equate the animal stocking rate and forage availability (Sharif et al., 2007). The management regimen in the scenario was
that does and their kids were grazed in the available area under an oil palm canopy for the entire period of production without supplemental feed. Kids were assumed to wean at an age of 90 d and lactation length was assumed to be equivalent to the kid weaning age. Breeding bucks outside of the herd were allowed to mate naturally with does in estrus. Conception and delivery rates were defined as 90 and 87%, respectively, for all genotypes. The pre- and postweaning mortality rates of kids were assumed to be as great as 8.0% due to extensive management. Horizontal and vertical movements for grazing animals under a good quality range were considered to occur and were set as described in AFRC (1998).

The forage DM production function under oil palm based on the age of the tree crop is given by Dahlan and Shahar (1992) as follows:

\[
DMY = a' \times AGE + b' \times AGE \times e^{c' \times AGE},
\]

where \( DMY \) is the DM yield (kg/ha); \( AGE \) is the palm age (yr); and \( a', b', \) and \( c' \) are coefficients. Equation 4 was fitted to the data of forage DM yield provided by Sharif et al. (2007) using the PROC NLIN of SAS. The estimated coefficients for the forage DM production function were 18.32, 2,905.14, and −0.39 for \( a', b', \) and \( c' \), respectively. Subsequently, the change in forage ME and metabolizability of the forage \( (g_s = 0.38) \) was estimated using data for forage nutritive quality given by Sharif et al. (2007). The stocking rates \([SR, \text{in AU/ha, where } \text{AU is animal unit (1 AU = a doe and her kids)}]\) by the production system were calculated as

\[
SR = \frac{ME_{\text{forage}}}{SUMME},
\]

where \( ME_{\text{forage}} \) is the available forage ME (MJ/ha) under the plantation canopy and \( SUMME \) is the total ME requirement (MJ) of the doe plus kids.

**RESULTS**

**Model Behavior**

In Figure 2, the simulated BW changes (kg) and ME intakes (MJ) for does by genotype over 8 parities are presented. The increased BW by pregnancy was not considered. The doe BW reached more than 90% of mature BW at 581, 524, and 429 d of age for the PI, F1, and BC breeds, respectively. After the growth stage, the ME intakes increased with the increase of the energy content of the fetus until kidding. After kidding, the ME intakes increased due to milk production for the lactating period. Figure 3 presents the simulated daily milk yield of does by crossbred genotype under base parameters over 8 parities. This reflects the effect of parity and crossbred genotype on milk yield.

The simulated performance of a PI doe under the base situation is presented in Table 5. The proportion of live does at the beginning of the cycle decreases due to the mortality and culling. The average ME intake increases until fourth parity along with the increase in ME\(_p\) and ME\(_s\), and thereafter it decreases with the decreases in the reproduction performance and milk production. The estimated average ME\(_m\) for a mature indigenous doe in this study was 6.07 MJ/d (BW = 28.8 kg). Sahlu et al. (2004) expressed the recommended ME requirements for maintenance using an NRC system, which they found to be 5.42 MJ/d for an indigenous doeling or nonparous doe weighing 30.0 kg. Devendra (1981) reported that the maintenance requirement for a goat in the tropics was 8.60 MJ/d (BW = 30.0 kg), and that this value was about 40 to 50% greater than the maintenance requirement for a penned goat in the tropics. The simulated results in this study indicated that the estimate fell between the published values, and that the model could provide a reasonable prediction of the energy requirements.

**Results of Application**

**Milk Production Scenario.** The simulated average total weights of products and ME intakes for milk production scenarios with concentrate supplementation are presented in Table 6. The values are expressed on a doe per production cycle basis. The results showed that the CMP\(_{BC}\) production system produced the most milk for sale and yielded the greatest milk PE and total PE, followed by the CMP\(_{F1}\) production system. This is because of the greater total milk yield and longer lactation length of the breeds in this scenario (Table 1). Although the PI production system yielded the least milk production for sale and least milk PE values among the systems, it also yielded a greater total PE value than the F1 and BC production systems. This is because PI does produce more kids at decreased ME intake. Surprisingly, the total PE values in the F1 and BC production systems were less than those of the other systems, and the value of the milk production for sale was also not great in these systems. This is because crossbred (F1 and BC) kids consumed more milk produced by PI and F1 does.

Table 7 presents the simulated productive efficiencies for various levels of concentrate supply during the lactation period. The PE increased with the increase in the level of concentrate supply within each production system. The CMP\(_{BC}\) and CMP\(_{F1}\) production systems sustained greater PE, whereas the F1 and BC production systems sustained decreased PE at all supplementation levels.

**Meat Production Scenario.** The estimated forage DM availability (DMY, kg/ha) under oil palm plantation and ME\(_{\text{forage}}\) (MJ/ha) value over 30 yr are shown in Figure 4. The forage DMY sharply decreased after the peak of 3 to 5 yr of planting due to canopy shade, a result which agreed with the findings of Sharif et al. (2007). The corresponding stocking rates for each of the crossbreeding production systems are presented.
in Figure 5. The SR of the first year for the PI, F1, and CMPF1 production systems were 5.8, 5.5, and 5.1 (AU/ha), respectively, and increased during the first 3 yr to the maximum rates of 8.0, 7.6, and 7.0 (AU/ha), respectively. After 5 yr of plantation, the stocking rates decreased sharply until 19 yr, and then gradually increased with the age of trees and the light penetration under the tree canopy. The production system using the single PI breed showed a greater stocking rate throughout the entire canopy age.

The simulated total outputs by crossbreeding system are presented in Table 8. The PI production system showed the greatest meat PE values because it had the greatest number of kids sold, whereas the CMPF1 production system showed the least meat PE value due to the reduced number of kids for sale and the greater ME intake of does.

**DISCUSSION**

Various simulation models with different purposes have been developed for beef cattle (Long et al., 1975; Lamb et al., 1992; Hirooka et al., 1998), dairy cattle (Congleton, 1984; Groen, 1988; Bryant et al., 2008), swine (Tess et al., 1983; McLaren et al., 1987), and sheep (Blackburn and Cartwright, 1987; Wang and Dickerson, 1991; Cannas et al., 2004). For goats, the first production model was described by Blackburn et al. (1987) as an extended version of a sheep model. The model was developed to simulate sheep performance for a wide array of genotypes in a wide variety of environments with managerial options and converted into a goat model by adjusting the equation parameters and input variables. Most simulation models in animal breeding fields have been developed to estimate...
the economic values (Tess et al., 1983; Groen, 1988; Wang and Dickerson, 1991; Hirooka et al. 1998). In this study, however, economic factors were not considered because there is no large difference between biological and economic efficiencies for goat production in developing countries. The purpose of this study simply compares the biological efficiencies among indigenous, crossbreeding, and composite production systems. For further research, the effects of the difference in genotype on internal and external parasites, vigorous of sire or semen, and heat tolerance should be considered for the model to be more adaptable to tropical conditions.

When a model is deterministic, the solutions obtained under various sets of circumstances are the direct result of the input data and the assumptions (Long et al., 1975). The main objective of the production model developed in this study was to assess the amount of goat products (milk and meat) and the productive efficiency of specific crossbreeding systems. The model is applicable to various crossbreeding schemes, environments, and management practices by changing the input variables. The model was first used to calculate the biological performance of individual animals by genotype, and then used to integrate the outputs of individual performances into a herd composition to predict the overall productivity for each production system based on the herd dynamics. Long et al. (1975) noted that the process of developing models and ex-

---

**Table 5.** Simulated performance of an indigenous (PI) doe under the base situation at individual level

<table>
<thead>
<tr>
<th>Item</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
</table>

1. Proportion of live does at the beginning of the cycle:
   - 0.796
   - 0.775
   - 0.495
   - 0.391
   - 0.308
   - 0.243
   - 0.191

2. Proportion of kids number weaned:
   - 1.36
   - 1.31
   - 1.10
   - 0.89
   - 0.65
   - 0.51
   - 0.40

3. BW at kidding, kg:
   - 22.8
   - 26.8
   - 28.2
   - 28.6
   - 28.7
   - 28.8
   - 28.8

4. Litter size at kidding:
   - 1.71
   - 2.09
   - 2.21
   - 2.28
   - 2.12
   - 2.10
   - 2.10

5. Average ME \(_m\) of the parity, MJ/d:
   - 5.47
   - 5.88
   - 6.01
   - 6.05
   - 6.07
   - 6.07
   - 6.07

6. Average ME intake of the parity, MJ/d:
   - 8.20
   - 8.98
   - 9.27
   - 9.30
   - 9.24
   - 9.11
   - 8.95

7. Accumulated milk yield of a doe in the parity, kg:
   - 81.0
   - 106.1
   - 116.4
   - 118.5
   - 116.0
   - 110.7
   - 103.8

8. Accumulated ME in the parity, MJ:
   - 81.9
   - 100.1
   - 106.0
   - 109.1
   - 101.7
   - 100.7
   - 100.7

9. Accumulated ME in the parity, MJ:
   - 460.1
   - 603.1
   - 661.1
   - 673.5
   - 659.3
   - 629.2
   - 590.0

---

**Figure 3.** Simulated daily milk yield of a doe by genotype under the base situation over 8 parities: PI = pure indigenous; F1 = first filial generation; BC = backcross.
Evaluating the results from simulation can identify areas of inadequate knowledge and the relative importance of various factors. The present study showed that the order of the ranking of genotypes differed between the 2 management systems (intensive milk production vs. extensive meat production), indicating the presence of a genotype by environment interaction. Bryant et al. (2005) stressed that an essential aim of a simulation model is to consider animal genotype and its interaction with the environment. Because wide variations can exist among environments in which goats are managed, such a simulation model will be a useful tool to find the most suitable feeding managements for each genotype.

Ensuring the success of a crossbreeding program is a crucial issue in developing countries in the tropics. Performance variables such as daily milk yield, total milk production, and lactation length among various crossbred goats have been compared to define better crossing combinations and to improve the quality of the local goat breeds (Montaldo et al., 1995; Prasad and Sengar, 2002). The present model simulated goat production systems in Malaysia as a typical example of a tropical region. Because indigenous goat breeds in Southeast Asia, East Africa, and the West Indies are considered to be a single racial group of Bezoar origin (Mason, 1981), numerous crossbreeding projects with similar objectives have been implemented in these regions, leading to common problems. Several authors have reported that not all crossbreeding programs in goats in developing countries under tropical conditions live up to expectations (Rischkowsky and Steinbach, 1997; Ayalew et al., 2003). The results of the model ap-

<table>
<thead>
<tr>
<th>Item</th>
<th>PI</th>
<th>F1</th>
<th>BC</th>
<th>CMP&lt;sub&gt;F1&lt;/sub&gt;</th>
<th>CMP&lt;sub&gt;BC&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of kids for sale</td>
<td>4.38</td>
<td>2.61</td>
<td>2.34</td>
<td>3.56</td>
<td>3.91</td>
</tr>
<tr>
<td>Sale BW of kids, kg</td>
<td>80.0</td>
<td>54.4</td>
<td>56.1</td>
<td>79.0</td>
<td>103.6</td>
</tr>
<tr>
<td>ME intake of kids, MJ</td>
<td>4,736.3</td>
<td>5,529.4</td>
<td>4,607.2</td>
<td>4,798.2</td>
<td>6,658.8</td>
</tr>
<tr>
<td>Culled BW of does, kg</td>
<td>19.6</td>
<td>19.6</td>
<td>22.3</td>
<td>22.3</td>
<td>24.4</td>
</tr>
<tr>
<td>ME intake of culled does, MJ</td>
<td>8,097.5</td>
<td>8,097.5</td>
<td>9,198.7</td>
<td>9,526.9</td>
<td>10,413.6</td>
</tr>
<tr>
<td>Milk production for sale, kg</td>
<td>90.3</td>
<td>103.7</td>
<td>119.9</td>
<td>229.3</td>
<td>307.9</td>
</tr>
<tr>
<td>Total BW for sale, kg</td>
<td>99.6</td>
<td>74.0</td>
<td>78.4</td>
<td>101.3</td>
<td>128.0</td>
</tr>
<tr>
<td>Total ME intake, MJ</td>
<td>12,833.8</td>
<td>13,626.8</td>
<td>13,806.0</td>
<td>14,325.1</td>
<td>17,072.5</td>
</tr>
<tr>
<td>Milk PE&lt;sup&gt;3&lt;/sup&gt;</td>
<td>7.04</td>
<td>7.61</td>
<td>8.68</td>
<td>16.01</td>
<td>18.03</td>
</tr>
<tr>
<td>Total PE&lt;sup&gt;4&lt;/sup&gt;</td>
<td>14.79</td>
<td>13.04</td>
<td>14.36</td>
<td>23.08</td>
<td>25.53</td>
</tr>
</tbody>
</table>

<sup>1</sup>The level of concentrate supply is assumed to be 10.0% of total DMI.
<sup>2</sup>See Table 4 for a description of the production systems. PI = pure indigenous; F1 = first filial generation; BC = backcross; CMP<sub>F1</sub> = F1 composite; CMP<sub>BC</sub> = BC composite breeds.
<sup>3</sup>Milk PE = milk production for sale (kg)/total ME intake × 10⁻³ (kg/GJ).
<sup>4</sup>Total PE = (total BW + milk production for sale; kg)/total ME intake × 10⁻³ (kg/GJ).
Application in this study indicated that the F1 production system had the least milk and total PE, followed by the BC system. This may partly explain the poor adaptability and sustainability of crossbreeding programs for the purpose of milk production in the tropics.

The potential of composite breeds for milk production in the tropics is generally greater due to the retention of heterosis. In cattle, some composite dairy breeds have been accepted in tropical regions (Kahi et al., 2000). The simulation results indicated that the CMPF1 and CMPBC production systems provided greater milk PE and total PE than other production systems. These results were consistent with the report of Devendra (2007), indicating that the F1 composite breed (Jermasia) is one of the successful examples for developing a new dual-purpose (meat and milk) breed in Malaysia. However, Devendra (2007) also reported that the development of a BC composite breed (Jermana) as a dairy breed was attempted, but the plan was abandoned due to the poor adaptability to the local environment and decreased performance of the animal. Moreover, establishing a composite breed requires a breeding population of sufficient size.

The results of the simulation for crossbreeding systems for meat production indicated that the PI production system had a better PE (meat PE) than the crossbreeding systems. This result implied that the indigenous goat production system had greater utility and good ability to thrive under extensive management. The greater fecundity and litter size of the indigenous breed also contributed to the result. Conkington et al. (2004) indicated that increased fecundity provides main influences on overall productivity and improvement of litter size benefitted positive economic value under both intensive and extensive sheep production systems in the harsh environment.

Among the simulated stocking rates in this application, the greatest value was 8.0 does with kids (/ha) of the indigenous production system in a plantation of 3-yr-old palms, and the least was 0.79 does with kids (/ha) in a CMPF1 production system under 17-yr-old palms. Dahlan (1992) simulated the stocking rate for goats in an oil palm plantation and reported that the stocking rate reached 1.8 goat/ha at 6 yr of palm age and decreased to 0.2 goat/ha at 24 yr of palm age, but Devendra (2009) indicated that the carrying capacity ranged from 25 to 30 indigenous goats per hectare in a plantation of 3 to 4-yr-old palms for a 2-yr cycle to 3 to 5 goats per hectare in plantation of over 7-yr-old palms. The difference in stocking rates between the studies might have been due to a variation in the estimation of forage ME availability due to the use of improved grasses and legumes, improved forage intake and palatability of goats, or both. The simulated stocking rates obtained in this study were intermediate between those of the previous studies.

As far as the authors are aware, this simulation study on goats is one of the very few of its kind applicable to the tropics. The results underscore the importance of having realistic production data to support the calculations.

In conclusion, a deterministic model for crossbreeding goat production was developed in the present study.

### Table 7. Predicted production efficiencies (PE) with varying dietary concentrate supply level for lactating does in the milk production scenario

<table>
<thead>
<tr>
<th>Item</th>
<th>Concentrate supply level, % of total DMI</th>
<th>PI</th>
<th>F1</th>
<th>BC</th>
<th>CMPF1</th>
<th>CMPBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk PE²</td>
<td>10.0</td>
<td>7.04</td>
<td>7.61</td>
<td>8.68</td>
<td>16.01</td>
<td>18.03</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td>7.36</td>
<td>7.94</td>
<td>9.16</td>
<td>17.02</td>
<td>19.17</td>
</tr>
<tr>
<td></td>
<td>30.0</td>
<td>7.68</td>
<td>8.26</td>
<td>9.63</td>
<td>18.01</td>
<td>20.28</td>
</tr>
<tr>
<td>Total PE³</td>
<td>10.0</td>
<td>14.79</td>
<td>13.04</td>
<td>14.36</td>
<td>23.08</td>
<td>25.53</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td>15.48</td>
<td>13.61</td>
<td>15.15</td>
<td>24.54</td>
<td>27.13</td>
</tr>
<tr>
<td></td>
<td>30.0</td>
<td>16.14</td>
<td>14.15</td>
<td>15.92</td>
<td>25.97</td>
<td>28.71</td>
</tr>
</tbody>
</table>

¹See Table 4 for a description of the production systems. PI = pure indigenous; F1 = first filial generation; BC = backcross; CMPF1 = F1 composite; CMPBC = BC composite breeds.

²Milk PE = milk production for sale (kg)/total ME intake × 10⁻³ (kg/GJ).

³Total PE = (total BW + milk production for sale; kg)/total ME intake × 10⁻³ (kg/GJ).
to evaluate the biological production efficiency for both milk and meat production in 5 crossbreeding production systems. The model was applied to evaluation of the crossbreeding program for an intensive milk production system and for a meat production system in an integrated tree crop system in Malaysia. The results indicated the utility of the indigenous goat production system and the decreased productivity in the F1 and BC production systems compared with the composite breed production systems.

**LITERATURE CITED**


**Table 8.** Simulated average number of kids for sale, total BW, and ME intake (kids plus culls) per doe and production efficiency (PE) for meat production by crossbreeding production system in meat production scenario

<table>
<thead>
<tr>
<th>Item</th>
<th>PI</th>
<th>F1</th>
<th>CMPF1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of kids for sale</td>
<td>3.69</td>
<td>3.28</td>
<td>2.97</td>
</tr>
<tr>
<td>Sale BW of kids, kg</td>
<td>73.4</td>
<td>75.9</td>
<td>73.6</td>
</tr>
<tr>
<td>ME intake of kids, MJ</td>
<td>6,309.7</td>
<td>7,238.9</td>
<td>6,558.7</td>
</tr>
<tr>
<td>Culled BW of does, kg</td>
<td>18.5</td>
<td>18.5</td>
<td>21.1</td>
</tr>
<tr>
<td>ME intake of culled does, MJ</td>
<td>10,251.9</td>
<td>10,251.9</td>
<td>12,532.1</td>
</tr>
<tr>
<td>Total BW for sale, kg</td>
<td>91.9</td>
<td>94.4</td>
<td>94.8</td>
</tr>
<tr>
<td>Total ME intake, MJ</td>
<td>16,561.5</td>
<td>17,490.7</td>
<td>19,090.8</td>
</tr>
<tr>
<td>Meat PE</td>
<td>5.55</td>
<td>5.40</td>
<td>4.97</td>
</tr>
</tbody>
</table>

1Assumed metabolizability of roughage (qr) = 0.38.

2See Table 4 for description of the production systems. PI = pure indigenous; F1 = first filial generation; CMPF1 = F1 composite.

3Meat PE = total BW (kg)/total ME intake × 10−3 (kg/GJ).


**APPENDIX A**

The following definitions were used throughout the appendices. The $x$ (subscript) represents genotype; $PI$ = pure indigenous; $F1$ = first filial generation; $BC$ = backcross; $y$ (subscript) represents sex; $moe = doe; m =$ male; $f =$ female; $m + f =$ the mean of male and female kids; and $t =$ age in days.

**Individual Level**

In this Appendix, it is assumed that the sex ratio is set to 0.5.

**Growth.** The daily postweaning BW change (kg) is estimated using the von Bertalanffy growth function (von Bertalanffy, 1957) as follows:

$$W_{x,y}(t) = A_{x,y} \left(1 - B_{x,y} e^{-k_{x,y} t/3}\right), \text{ } [A1]$$

where $W_{x,y}(t)$ is the BW at age $t$, $A_{x,y}$ is the mature weight, $B_{x,y}$ is the constant of integration, and $k_{x,y}$ is the maturing rate. Birth weight ($BWT_{x,y}$, kg) is the BW at age 0 and $BWT_{x,m+f}$ is the predicted mean birth weight of male and female kids:

$$BWT_{x,y} = W_{x,y}(0), \text{ } [A2]$$

$$BWT_{x,m+f} = (BWT_{x,m} + BWT_{x,y}) \times 0.5. \text{ } [A3]$$

Daily BW gains in the pre- and postweaning periods [$DG_{x,y}(t)$, kg/d] are estimated as

$$DG_{x,y}(t) = (WW_{x,y} - BWT_{x,y})/\text{twean}, \text{ } (t \leq \text{twean}) \text{ and }$$

$$DG_{x,y}(t) = 3k_{x,y} W_{x,y}(t) \times \left[\left(W_{x,y}(t)/A_{x,y}\right)^{-1/3} - 1\right], \text{ } (t > \text{twean}), \text{ } [A4]$$

where "twean" is the weaning age.

**Milk Production.** The daily milk yield (kg/d) is estimated based on the William lactation curve function (Williams, 1993):

$$MY_{x,milk}(1) = A_0 \exp\left[\frac{B(1 + n'_\text{milk}}{2}n'_\text{milk} + \chi_\text{milk}^2 - 1.01}{n'_\text{milk}}\right], \text{ } [A5]$$
where \( MY_{x,n_{milk}}(1) \) is the daily milk yield (kg) at first parity \( (= 1) \), \( n_{milk} \) is the day of lactation (post-parturition), \( n_{milk}' \) is \((n_{milk} - 150)/100\), \( A_x \) is the scale parameter, parameter \( B \) is \(-0.56436\), and parameter \( C \) is \(0.00690\) (Oishi et al., 2008). Using parameters \( B \) and \( C \), the parameter \( A_x \) is estimated as

\[
A_x = TMY_x/\left\{ \sum_{n_{milk}=1}^{t_{lact}} \exp \left[ -0.56436(1 + n_{milk}' / 2)n_{milk}' \right] + 0.00690 \times n_{milk}'^2 - 1.01 / n_{milk}' \right\},
\]

where \( TMY_x \) is the total milk yield (kg) at the first parity by genotype defined by users and \( t_{lact} \) is the lactation length. The ratio of average daily milk yield in different parities \([m_{par}(par)]\) is calculated using Wood’s function (Wood, 1967) as

\[
m_{par}(par) = A' \times \exp^{-C' \times \text{par}},
\]

where \( \text{par} \) is the number of parities, and the estimated parameters \( A', B', \) and \( C' \) are \(1.19245, 0.62117, \) and \(0.16002\), respectively (Oishi et al., 2008). Therefore, the corrected daily milk yield (kg/d) by parity is expressed as

\[
MY_{x,n_{milk}}(par) = m_{par}(par) \times MY_{x,n_{milk}}(1)
\]

\[
= MY_x(t)[t_{part}(t) < t \leq t_{part}(t) + t_{lact}],
\]

where \( t_{part}(t) \) is the age at parturition as follows:

\[
t_{part}(t) = t_{mtfst} + t_{cl}(par - 1) + t_{preg},
\]

where \( t_{mtfst} \) is the age at first mating \((= 270 \text{ d})\), \( t_{cl} \) is the length of the reproduction cycle \((= 240 \text{ d})\), \( \text{par} \) is the number of parities, and \( t_{preg} \) is the gestation length \((= 150 \text{ d})\).

**ME Requirement.** The estimation of ME requirement for each production stage is mainly based on AFRC (1998) and expressed in megajoules. The daily ME\(_m\) requirement \([ME_{m,x,y}, \text{MJ/d}]\) is the sum of the fasting metabolism \((F_{x,y}, \text{MJ/d})\) and activity \((AC_{x,y,y}, \text{MJ/d};\) see Table 3 for description of adjustment of activity) as follows:

\[
F_{x,y}(t) = 0.315 \times W_{x,y}(t)^{0.75},
\]

\[
AC_{x,y}(t) = (Ehrz \times hrz/10^6 + Eort \times vrt/10^6 + Estr/10^3 + Echg \times chg/10^3) \times W_{x,y}(t),
\]

\[
ME_{m,x,y}(t) = [F_{x,y}(t) + AC_{x,y}(t)] / k_m,
\]

\[
k_m = 0.35q_e + 0.503,
\]

where \( k_m \) is the efficiency of utilization of ME\(_m\) given by AFRC (1998), \( q \) is the metabolizability of diet, \( v \) is the type of diet, \( E \) is additional energy cost, \( hrz \) is horizontal movement, \( vrt \) is vertical movement, \( strn \) is standing, and \( chg \) is 1 position change. The energy content of BW gain \((EV_{g,x,y}, \text{MJ/kg})\) is given by AFRC (1993) as

\[
EV_{g,x,y}(t) = 4.972 + 0.3274 \times W_{x,y}(t). \quad [A14]
\]

Thus, the ME\(_g\) of nonlactating goats \([ME_{g,x,y}, \text{MJ/d}]\) is calculated as

\[
ME_{g,x,y}(t) = DG_{x,y}(t) \times EV_{g,x,y}(t) / k_f \quad [A15]
\]

\[
k_f = 0.78q_e + 0.006, \quad [A16]
\]

where \( k_f \) is the efficiency of utilization of ME\(_g\) and ME for fattening (AFRC, 1998). The ME requirement for pregnancy \([ME_{p_y}(t), \text{MJ/d}]\) is estimated using the function by Bosman et al. (1997):

\[
ME_{p_y}(t) = BWT_x \times LS_x(par) \times 10^{[0.597 - 7.819 \times \exp(-0.0175 \times t_{preg}(t))]}, \quad [A17]
\]

where \( \text{par} \) is the number of parities, subscript \( x \) is the genotype of doe, subscript \( y \) is the genotype of kid, \( LS_x(par) \) is the litter size of does by parity, and \( t_{preg}(t) \) is the number of days pregnant as follows:

\[
t_{preg}(t) = t - (t_{cl} \times \text{par} + t_{mtfst}). \quad [A18]
\]

The ME requirement for lactation \((ME_{t,y}, \text{MJ})\) is based on the energy content of the milk produced by a doe in a parity. The energy value of milk \((\text{MJ/kg})\) is predicted from milk fat concentration (AFRC, 1998) as

\[
EV_{milk_x} = 1.309 + 0.04925 \times mfat_x. \quad [A19]
\]

where \( EV_{milk_x} \) is the energy value of milk (MJ/kg) and \( mfat_x \) is the milk fat concentration (g/kg). The net energy for milk produced by a doe \((\text{MJ/d})\) is expressed as:

\[
Emilk_x(t) = EV_{milk_x} \times MY_x(t), \quad [A20]
\]

\[
ME_{t,y}(t) = Emilk_x(t) / k_t, \quad [A21]
\]

\[
k_t = 0.35q_e + 0.420, \quad [A22]
\]

where \( MY_x(t) \) is the daily milk yield (see Eq. A8) and \( k_t \) is the efficiency of utilization of ME\(_t\) (AFRC, 1998). The ME\(_g\) requirement \((\text{MJ/d})\) in a lactating doe is corrected by AFRC (1998) as

\[
ME_{g,doe}(t) = DG_{d,doe}(t) \times EV_{g,d,doe}(t) / 0.95k_i. \quad [A23]
\]

Accordingly, the daily ME requirement of an individual goat \((\text{MJ/d})\) is calculated as
Estimation of Energy Intake from Dietary Feed for Preweaning Kids. The energy requirements of kids are assumed to be supplied only by the milk of their doe from birth to 7 d of age and, thereafter, both the milk of the doe and dietary supplementation are assumed to provide energy resources until the weaning age. It is also assumed that the milk of the Doe is completely consumed and deficiencies in meeting energy requirements are made up for by dietary supplementation. The expressions for differences between the NE requirements of kids and the need for milk produced by the Doe are estimated from the differences between the NE requirements of kids and the NE for milk produced by the Doe. Thus, the efficiency of ME utilization of dietary supplementation for maintenance and production and its net energy value (NEpl, MJ/kg of DM) are calculated as follows:

\[
\text{NEpl}_{x,m} = \frac{\text{NE}_{x,m} + \text{NE}_{x,f} - \text{Emilk}_x}{0.5},
\]

where \(\text{NE}_{x,m}\) is the NE intake from dietary supplementation, \(\text{NE}_{x,f}\) is the NE intake from the Doe, and \(\text{Emilk}_x\) is the energy value of milk (MJ/kg of DM). Thus, the energy requirements of kids per Doe, \(nkd_{x} / \text{par}\), is the litter size of does by parity (see Eq. 1 in the text) and \(\text{par}\) is the number of parities. Accordingly, the average ME intake from dietary supplementation \(\text{MEpl}_{x,m} / \text{par}\) of total kids can be expressed as

\[
\text{MEpl}_{x,m} = \frac{\text{ME}_{x,m} + \text{ME}_{x,f} - \text{Emilk}_x}{0.5},
\]

The daily NE requirements (MJ/d) of \(x\) genotype male \((\text{NE}_{x,m})\) and female \((\text{NE}_{x,f})\) kids are calculated as

\[
\text{NE}_{x,m} = F_x + AC_{x,m}(t) + DG_{x,m}(t) \times EV_{g_{x,m}}(t),
\]

and

\[
\text{NE}_{x,f} = F_x + AC_{x,f}(t) + DG_{x,f}(t) \times EV_{g_{x,f}}(t),
\]

where \(F_x\) is the fasting metabolism, \(AC_{x,y}\) is the total energy costs of activity (see Table 3), \(DG_{x,y}\) is the daily BW gains, \(TNE_{x,m} / \text{par}\) is the total net energy requirement of kids per Doe, \(nkd_{x} / \text{par}\) is the litter size of does by parity (see Eq. 1 in the text) and \(\text{par}\) is the number of parities. Accordingly, the average ME intake from dietary supplementation \(\text{MEpl}_{x,m} / \text{par}\) of total kids can be expressed as

\[
\text{MEpl}_{x,m} = \frac{\text{ME}_{x,m} + \text{ME}_{x,f} - \text{Emilk}_x}{0.5},
\]

Thus, the efficiency of ME utilization of dietary supplementation for maintenance and production and its net energy value (NEpl, MJ/kg of DM) are calculated as follows:

\[
\text{NEpl} = \frac{\text{ME}_{x,m} + \text{ME}_{x,f} - \text{Emilk}_x}{0.5},
\]

If \(TNE_{x,m} / \text{par}\) is more than the energy value of milk produced by the Doe in the parity \(\text{Emilk}_x / \text{par}\), the amount of dietary supplementation intake \(\text{DMsp}_{x,m} / \text{par}\) can be estimated as

\[
\text{DMsp}_{x,m} / \text{par} = \frac{\text{NE}_{x,m} + \text{NE}_{x,f} - \text{Emilk}_x}{0.5},
\]

and if \(TNE_{x,m} / \text{par}\) is less than \(\text{Emilk}_x / \text{par}\), then

\[
\text{DMsp}_{x,m} / \text{par} = 0.
\]

Finally, the ME intakes of individual kids from dietary supplementation \(\text{MEpl}_{x,m} / \text{par}\) are calculated as

\[
\text{MEpl}_{x,m} = \frac{\text{ME}_{x,m} + \text{ME}_{x,f} - \text{Emilk}_x}{0.5},
\]

where \(nkd_{x} / \text{par}\) is the litter size of does by parity (see Eq. 1 in the text) and \(\text{par}\) is the number of parities. Accordingly, the average ME intake from dietary supplementation \(\text{MEpl}_{x,m} / \text{par}\) of total kids can be expressed as

\[
\text{MEpl}_{x,m} = \frac{\text{ME}_{x,m} + \text{ME}_{x,f} - \text{Emilk}_x}{0.5},
\]

In addition, the milk consumption \((\text{csmmlk}_{x,m} / \text{par})\) of total kids is estimated as

\[
\text{csmmlk}_{x,m} / \text{par} = \frac{\text{ME}_{x,m} + \text{ME}_{x,f} - \text{Emilk}_x}{0.5},
\]

where \(\text{ME}_{x,m} + \text{ME}_{x,f} - \text{Emilk}_x\) is the total net energy requirement of kids per Doe, \(nkd_{x} / \text{par}\) is the litter size of does by parity (see Eq. 1 in the text) and \(\text{par}\) is the number of parities. Accordingly, the average ME intake from dietary supplementation \(\text{MEpl}_{x,m} / \text{par}\) of total kids can be expressed as

\[
\text{MEpl}_{x,m} = \frac{\text{ME}_{x,m} + \text{ME}_{x,f} - \text{Emilk}_x}{0.5},
\]

Thus, the efficiency of ME utilization of dietary supplementation for maintenance and production and its net energy value (NEpl, MJ/kg of DM) are calculated as follows:

\[
\text{NEpl} = \frac{\text{ME}_{x,m} + \text{ME}_{x,f} - \text{Emilk}_x}{0.5},
\]
\[ \text{csmilk}_{x,m}(t) = \text{csmilk}_{x,m+1}(t) \times \left( \frac{\text{NE}_{x,m}(t)}{[\text{NE}_{x,m}(t) + \text{NE}_{x,m+1}(t)]/\left[0.5 \times L S_x(par)\right]} \right) \]
\[ \text{csmilk}_{x,f}(t) = \text{csmilk}_{x,m+1}(t) \times \left( \frac{\text{NE}_{x,m}(t)}{[\text{NE}_{x,m}(t) + \text{NE}_{x,m+1}(t)]/\left[0.5 \times L S_x(par)\right]} \right). \]

**APPENDIX B**

**Herd Dynamics**

**B-1. Replacement Rate, Production Outputs, and ME Intake.** In this Appendix, it is assumed that the sex ratio is set to 0.5. The total number of kids produced by a doe throughout her whole life \((TNK_x)\) is accumulated as

\[ TNK_x = \sum_{i=1}^{\text{parmax}} n\text{kid}_x(i), \quad \text{[B1]} \]

where \(\text{parmax}\) is maximum parity and \(n\text{kid}_x(i)\) is the number of kids produced by a doe in each parity \((i)\) (see Eq. 1 in the text). Accordingly, the number of female kids (to move to the doe module) is expressed as

\[ n\text{fkid}_x = TNK_x \times \text{surv}_x(t\text{cull}) \times 0.5, \quad \text{[B2]} \]

where \(\text{surv}_x\) is the survivability of a kid at the age to be sold or replaced \((t\text{cull} = 270 \text{d})\). The survivability is calculated as

\[ \text{surv}_x(t) = \left[1 - w\text{mort}_x(t)\right]^{t/t\text{wean}} (t \leq t\text{wean}) \quad \text{and} \]

\[ \text{surv}_x(t) = \left[1 - w\text{mort}_x(t)\right] \times \left[1 - \text{mort}_x(t)\right]^{1/365} \times [t/t\text{wean}^t] (t > t\text{wean}), \quad \text{[B3]} \]

where \(w\text{mort}_x\) is the preweaning mortality, \(\text{mort}_x\) is the yearly postweaning mortality, and \(t\text{wean}\) is the weaning age. The replacement rate \((r_x)\) is defined as

\[ r_x = 1/n\text{fkid}_x. \quad \text{[B4]} \]

**Outputs of Kid.** The number of female kids to be sold \((\text{cullkid}_{x,f})\) is calculated as

\[ \text{cullkid}_{x,f} = TNK_x \times \text{surv}_x(t\text{cull}) \times 0.5, (1 - r_x), \quad \text{[B5]} \]

and all male kids produced are assumed to be sold.

\[ \text{cullkid}_{x,m} = TNK_x \times \text{surv}_x(t\text{cull}) \times 0.5. \quad \text{[B6]} \]

Thus, the total number of kids for sale \((T\text{cullkid}_x)\) is expressed as

\[ T\text{cullkid}_x = \text{cullkid}_{x,f} + \text{cullkid}_{x,m}. \quad \text{[B6]} \]

Similarly, the total sale weight of kids \((T\text{kidw}_x, \text{kg})\) is given as

\[ T\text{kidw}_x = \text{cullkid}_{x,f} \times \text{kidw}_f + \text{cullkid}_{x,m} \times \text{kidw}_m, \quad \text{[B7]} \]

where \(\text{kidw}_f\) is the BW of a kid at the age to be culled \((t\text{cull} = 270 \text{d})\) as estimated in the kid module.

**Outputs and ME Intakes of Does.** The number of does starts as 1 at the first day in the doe module \((t\text{tf}\text{fst})\) and decreases with survivability and culling. The daily change in the number of does \([n\text{dam}_x(t)]\) is expressed as

\[ n\text{dam}_x(t) = \begin{cases} 1, & (t = t\text{tf}\text{fst}), \\ n\text{dam}_x(t) = 1 \times \text{surv}_x(t) \times \text{concr}_x, & (t\text{tf}\text{fst} < t \leq t\text{tf}\text{fst} + t\text{preg}), \\ n\text{dam}_x(t) = 1 \times \text{surv}_x(t) \times \left(\text{concr}_x \times \text{delr}_x\right)^{\text{ncycl}}, & (t > t\text{tf}\text{fst} + t\text{preg}), \end{cases} \quad \text{[B8]} \]

where \(\text{surv}_x(t)\) is survivability (see Eq. B3), \(\text{concr}_x\) is conception rate, \(t\text{preg}\) is gestation length, \(\text{delr}_x\) is delivery rate, and \(\text{ncycl}\) is the number of reproduction cycles. Culled BW \((\text{cullw}_x, \text{kg})\) of does by parity are calculated as

\[ \text{cullw}_x(0) = w_x,\text{doe}(t) \times n\text{dam}_x(t) \]

\[ \times (1 - \text{concr}_x), (t = t\text{tf}\text{fst}), \]

\[ \text{cullw}_x(1) = w_x,\text{doe}(t) \times n\text{dam}_x(t) \times (1 - \text{delr}_x), \]

\[ (t = t\text{tf}\text{fst} + t\text{preg}), \]

\[ \text{cullw}_x(\text{par}) = w_x,\text{doe}(t) \times n\text{dam}_x(t) \]

\[ \times (1 - \text{concr}_x \times \text{delr}_x), [t = t\text{part}(t) + t\text{wean}], \quad \text{[B9]} \]

where \(t\text{part}(t)\) is the age at parturition (see Eq. A9). The total culled BW of does \((T\text{cullw}, \text{kg})\) is then calculated as

\[ T\text{cullw}_x = \sum_{i=0}^{\text{parmax}} cullw_x(i). \quad \text{[B10]} \]

The daily ME requirements of a doe \((\text{ME}_{x,\text{doe}}, \text{MJ})\) over a lifetime \([t = t\text{tf}\text{fst}\quad \text{to the final day of the maximum parity \((t\text{final})\); \text{MJ}}\) are accumulated in the doe module as

\[ T\text{me}_x(t) = \sum_{t = t\text{tf}\text{fst}}^{t\text{final}} \text{ME}_{x,\text{doe}}(t) \times n\text{dam}_x(t). \quad \text{[B11]} \]

Thus, the accumulated ME requirements of culled does by parity \([\text{cullme}_x(\text{par}), \text{MJ}]\) are calculated as

\[ \text{cullme}_x(0) = T\text{me}_x(t) \times (1 - \text{concr}_x), (t = t\text{tf}\text{fst}), \]
\[ cullme_\alpha(t) = Tnme_\alpha(t) \times (1 - delr_\alpha), \]
\[ (t = tmntst + tspreg), \]
\[ cullme_\alpha(par) = Tnme_\alpha(t) \times (1 - concr_\alpha \times delr_\alpha), \]
\[ (t = tmpart(t) + tmeam). \]

The equation used to calculate the total ME intake of the culled doe is shown in Eq. 3 in the text. The calculated milk consumption (kg) of kids of a doe by parity is accumulated as
\[
Tcsmlk_{x,m+1} = \sum_{i=1}^{parmax} \frac{0.5 \times nkid_\alpha(i) \times [csmlk_{x,m}(t) + csmlk_{x',f}(t)]}{(1 - delr_\alpha)},
\]
where subscript \( x \) is the genotype of the doe, subscript \( x' \) is the genotype of the kid, \( Tcsmlk_{x,m+1} \) is the total milk consumption of all kids, \( nkid_\alpha(par) \) is the litter size of does by parity, \( csmlk_{x,m}(t) \) is the daily milk consumption of a male kid, and \( csmlk_{x',f}(t) \) is that of a female kid (Eq. A38). The total milk production of a doe over her lifetime \( (Tmlkp_\alpha \text{ kg}) \) is calculated from the daily milk yield of a doe \( [MY_\alpha(t); \text{Eq. A8}] \) and the number of does \( [ndam_\alpha(t); \text{Eq. B8}] \) as
\[
Tmlkp_\alpha = \sum_{t=tmntst+tspreg}^{final} MY_\alpha(t) \times ndam_\alpha(t). \]  

The amount of milk production for sale \( (smlk, \text{kg}) \) is the difference between Eq. B14 and B13:
\[
smlk_\alpha = Tmlkp_\alpha - Tcsmlk_{x,m+1}. \]

**B.2. Herd-Level Crossbreeding System.** The outputs calculated in B-1: total number of kids for sale (Eq. B6), total sale weight of kids (Eq. B7), total culled weight of does (Eq. B10), milk production for sale (Eq. B15), and the total ME intakes of doe and kids (see Eq. 2 and 3 in the text) are used in this section.

**F1 System.** The proportion of animals in each herd is equal to the proportion of does (Figure A1). Thus, the total performances of does and kids are calculated as
\[
output_{doc} = r_{PF} \times output_{PI,doc} + (1 - r_{PF}) \times output_{PI,doc}, \]
\[
output_{kid} = r_{PF} \times output_{PI,m} + (1 - r_{PF}) \times (output_{PI,m} + output_{PI,f}),
\]
where \( output_{x,y} \) is the outputs mentioned above and \( r_{PF} \) is the replacement rate of pure indigenous \( (r_{PF}) \) and total number of does \( (Tndam) \) (see Figure A1):
\[
Tndam = r_{PF} \times nkid_{PF} + (1 - r_{PF}) \times nkid_{PI} + (1 - r_{PF}) \times nkid_{FI},
\]
where \( nkid_\alpha \) is the number of does (see Eq. B2). Accordingly, the total performances of does and kids are calculated as
\[
output_{doc} = (r_{PF}/Tndam) \times output_{PI,doc} + [(1 - r_{PF})/Tndam] \times output_{PI,doc} + [(1 - r_{PF})/Tndam] \times output_{PI,doc},
\]
\[
output_{kid} = (r_{PF}/Tndam) \times output_{PI,m} + [(1 - r_{PF})/Tndam] \times output_{PI,m} + [(1 - r_{PF})/Tndam] \times output_{PI,m}, \]
where \( output_{x,y} \) is the outputs mentioned above.

**APPENDIX C**

**Calculation of Total Metabolizability for Lactating Does with Different Proportions of Concentrate Supply in a Milk Production Scenario**

The amount of concentrate supply is the proportion to the DMI of a doe and is defined as
\[
x = DM_{con}/(DM_{con} + DM_{rough}), \]
where \( x \) is the proportion of concentrate supply in total DMI \((\text{kg/d})\), \( DM_{con} \) is the DMI \((\text{kg/d})\) of concentrate, and \( DM_{rough} \) is the DMI \((\text{kg/d})\) of roughage. Thus, the proportion of \( DM_{rough} \) to \( DM_{con} \) is expressed by \( x \) as
\[
DM_{rough}/DM_{con} = (1 - x)/x. \]

Because the metabolizability of feeds is defined as the proportion of ME in the GE of the total diet \((q = \text{ME/GE})\) and the mean value of the GE is assumed to be 18.4 MJ/kg of DM (AFRC, 1993), the relationships between ME and DM of each diet are expressed as
\[
ME_{rough} = DM_{rough} \times 18.4 \times q_r, \]
\[
ME_{con} = DM_{con} \times 18.4 \times q_c, \]
where \( ME_{rough} \) (MJ) is the ME intake from roughage, \( ME_{con} \) (MJ) is the ME intake from concentrate, \( q_r \) is the metabolizability of roughage, and \( q_c \) is the metabolizability of concentrate. The metabolizability of total diet \((q)\) can be represented by the proportions of concentrate and roughage in total ME intake as
The substitution of Eq. C3 and C4 into Eq. C5 gives

\[ q_t = q_r \times \left[ \frac{ME_{rough}}{ME_{rough} + ME_{con}} \right] + q_c \times \left[ \frac{ME_{con}}{ME_{rough} + ME_{con}} \right] \]

The value of \( q_t \) can be obtained by substituting Eq. C2 into Eq. C6 and expressed as

\[ q_t = q_r \times \left[ \frac{q_r \times \left( 1 - \frac{1}{x} \right) + q_c \times \left( 1 - \frac{1}{x} \right)}{q_r \times \left( 1 - \frac{1}{x} \right) + q_c \times \left( 1 - \frac{1}{x} \right)} \right] + q_c \times \left[ \frac{q_r \times \left( 1 - \frac{1}{x} \right) + q_c \times \left( 1 - \frac{1}{x} \right)}{q_r \times \left( 1 - \frac{1}{x} \right) + q_c \times \left( 1 - \frac{1}{x} \right)} \right] \]