An individual-based model simulating goat response variability and long term herd performance

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Supplementary material online

Appendix B. Description of the animal sub-model

The animal sub-model incorporates two sub-systems: the regulating sub-system (RegS) and the operating sub-system (OpS). RegS simulates theoretical dynamics which represents the priorities between physiological functions of growth, pregnancy, lactation, body reserves mobilization and reconstitution. Figure S1, Table S1 and Table S2 summarize RegS functioning. The dimensionless dynamics generated by RegS are transmitted to OpS. This sub-system simulates energy and material flows associated to physiological functions depending on the available net energy of the diet. An energy flow is defined by a potential part defined by RegS and a deviation from this potential due to the partitioning of dE, the differential of energy between potential energy intake (defined by RegS) and actual intake (defined by diet). This principle is illustrated on Figure S2 and all equations are presented in Table S3. At each time step, energy is conserved:

$$EIN_{Diet} = E_{GR} + E_{GU} + E_{MNT} + E_{ST} + E_{MY} - E_{MOB}$$
$$\Leftrightarrow EIN_{Diet} = E_{GR} + E_{GU} + E_{MNT} + (E_{STp}+q_2.dE) + (E_{MYp}+r_2.dE) - (E_{MOBp}+p_2.dE)$$

As:

$$E_{INp} = E_{GR} + E_{GU} + E_{MNT} + E_{STp} + E_{MYp} - E_{MOB_p}$$

The relation becomes:

$$EIN_{Diet} = EIN_p + (q_2 \cdot dE) + (r_2 \cdot dE) - (p_2 \cdot dE) \Leftrightarrow EIN_{Diet} = EIN_p + dE \cdot (q_2 + r_2 - p_2) \Leftrightarrow q_2 + r_2 - p_2 = 1$$

Hence, the relation between p_2, q_2 and r_2 ensures the energy conservation between inputs and outputs. The partitioning of dE is depending on the relative priority of physiological functions (Figure S3) and on body reserves level. Energy flows are traduced into material flows by energy conversion parameters (Table S5). Hence, the animal sub-model simulates individual performances (body weight and milk) depending on energy from the diet (Table S4). Finally, Table S6 illustrates the variables which have no biological meaning but which enable connection with management sub-model.

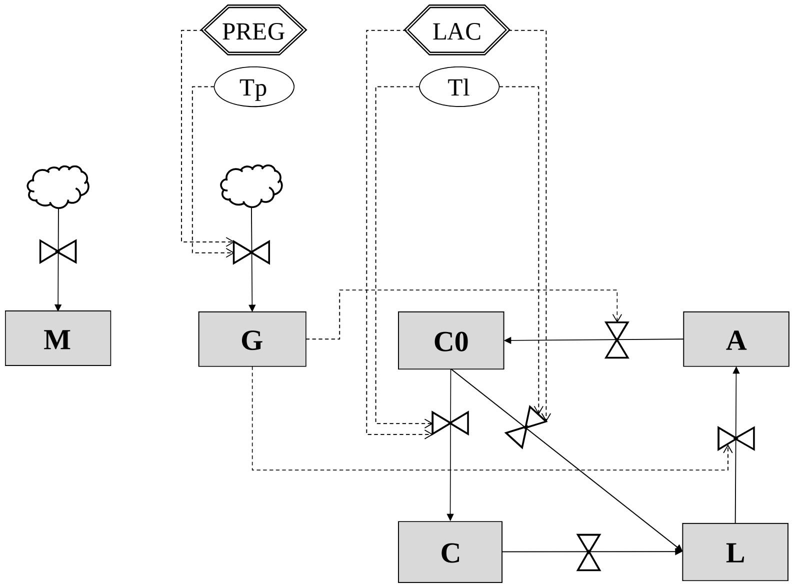


Figure S1 Regulating sub-system of the animal model in SIGHMA. Theoretical hormones are represented by state variables with M = growth, G = gestation, C = catabolism, L = lactation and A = anabolism. C_0 is a compartment ensuring the accumulation of the dimensionless material circulating through C, L and A. PREG and LAC are Boolean variables reflecting pregnancy and lactation status. Tp and Tl are control variables related to the physiological time of pregnancy and the physiological time of lactation.

Table S1 *List of the elements of the model*

Element name	Description
A	Meta-hormone of anabolism
BWp	Potential empty body weight
BW	Empty body weight
BR	Body reserves
BWb	Body weight at birth
BWm	Mature body weight
C	Meta-hormone of catabolism
C0	Accumulation compartment
dE	Energy differential between potential energy intake and real intake
DAT_{CON}	Conception
DAT_{NXTKID}	Next kidding
DAT_{PRVKID}	Previous kidding
DAT_{DRY}	Drying off
E_{GR}	Energy for growth
E_{GU}	Energy for Gravid uterus
E_{MNT}	Energy for Maintenance
E_{MBp}	Potential energy for mobilisation
E_{STp}	Potential energy for reconstitution
E_{MYp}	Potential energy for milk exportation
E_{INp}	Potential energy for intake
E_{MB}	Energy for Mobilisation
E_{ST}	Energy for Reconstitution
E_{MY}	Energy for Milk exportation
E_{diet}	Energy ingested from diet
E_{MAJ}	Energy increase due to digestive interactions
EINdiet	Available energy from diet
EV_{GU}	Energy value for the gain of 1 kg of gravid uterus
EV_{GR}	Energy value for the gain of 1 kg of body weight
EV_{MB}	Energy value of the mobilisation of 1 kg of body weight
EV_{ST}	Energy value of the reconstitution of 1 kg of body weight
EV_{FCMY}	Energy value of 1 kg of fat corrected milk
EV_{UFL}	Energy value of 1 UFL (1700 Mcal)

ExtLac	Extended lactation status
f_{C0C}	Flow from C_0 to C
f_{C0L}	Flow from C_0 to L
f_{CL}	Flow from C to L
f_{LA}	Flow from L to A
f_{AC0}	Flow from A to C_0
$FCMY_p$	Potential fat corrected milk yield
FCMY	Fat corrected milk yield
G	Meta-hormone of gestation
GU_i	
GU_a	Parameters of the equation for the gestation meta-hormone
GU_b	
GU_c	
GU	Gravid uterus
INTCAP	Intake capacity
k_M	Parameter of the growth meta-hormone equation
k_{C0C}	Parameter of the flow from C_0 to L
k_{C0L}	Parameter of the flow from C_0 to L
k_{CL}	Parameter of the flow from C to L
k_{LA}	Parameter of the flow from L to A
k_{GA}	Parameter of the flow from G to A
k_{AC0}	Parameter of the flow from A to C_0
k_{GC0}	Parameter of the flow from G to C_0
k_{MB}	Scaling variable to link body weight dynamic and production potential
k_{CA}	Scaling variable to link body weight mobilisation and reconstitution
k_{MY}	Scaling variable to link meta-hormone of lactation and milk production
L	Meta-hormone of lactation
LAC	Lactation status
LL	Lactation length
LS	Litter size
M	Growth meta-hormone
MY_p	Potential milk yield
MY	Milk yield
ME	Management entity number
MG	Mating group number

NLAC	Lactation number
$NLAC_{effect}$	Lactation number effect
NumGoat	Individual number
ON	Living status
PREG	Pregnancy status
p	Partitioning coefficient related to potential mobilisation
p_2	Partitioning coefficient related to mobilisation (modulation of p by body reserves level)
pctBR	Proportion of body reserves
POT	Milk production potential
pctBRp	Potential percentage of body reserves
q	Partitioning coefficient related to potential reconstitution
q_2	Partitioning coefficient related to reconstitution (modulation of q by body reserves level)
QDi	Distributed quantity of feedstuff i
QIi	Intake of feedstuff i
r	Partitioning coefficient related to potential milk production
r_2	Partitioning coefficient related to milk production (modulation of r by body reserves level)
Tl	Lactation time (days)
Tp	Pregnancy time (days)
TreshDead	Threshold used in the stochastic process representing mortality
UEi	Fill unit of feedstuff i
UFi	Energy value of feedstuff i
WKLAC	Lactation week
X	Theoretical function modulating q
Z	Theoretical function modulating p

Table S2 *Regulating sub-system: variables*

Variable	Description	Equation
Theoretical hormone		
A	Anabolism	$\frac{dA}{dt} = -f_{AC0} + f_{LA}$
C	Catabolism	$\frac{dC}{dt} = f_{C0C} - f_{CL}$
L	Lactation	$\frac{dL}{dt} = f_{C0L} + f_{CL} - f_{LA}$
C_0	Accumulation compartment	$\frac{dC0}{dt} = -f_{C0C} - f_{C0L} + f_{AC0}$
M	Growth	$\frac{dM}{dt} = -k_M \cdot M$
G	Gestation	$\frac{dG}{dt} = GU_i \cdot \exp(GU_a \cdot Tp^2 + GU_b \cdot Tp + GU_c) \cdot ((2 \cdot GU_a \cdot Tp + GU_b)^2 + 2 \cdot GU_a) \cdot PREG$
Flow		
f_{C0C}	C_0 to C	$f_{C0C} = \begin{cases} k_{C0} \cdot C0 \cdot LAC & \text{if} \quad Tl \in [1,2] \\ 0 & \text{else} \end{cases}$
f_{C0L}	C_0 to L	$f_{C0L} = \begin{cases} k_{C0L} \cdot C0 \cdot LAC & \text{if} \quad Tl \in [1,2] \\ 0 & \text{else} \end{cases}$
f_{CL}	C to L	$f_{CL} = k_{CL} \cdot C \cdot ON$
f_{LA}	L to A	$f_{LA} = L \cdot (k_{LA} + k_{GA} \cdot G) \cdot ON$
f_{AC0}	A to C_0	$f_{AC_0} = (A \cdot (k_{AC_0} + k_{GC_0} \cdot G)) \cdot ON$
Control		
ON	Living status	$ON = \begin{cases} 1 & \text{at} \quad \text{birth} \\ 0 & \text{at} \quad \text{death} \end{cases}$
LAC	Lactation status	$LAC = \begin{cases} 1 & \text{at} \quad \text{kidding} \\ 0 & \text{at} \quad \text{drying–off} \end{cases}$
PREG	Pregnancy status	$PREG = \begin{cases} 1 & \text{at} \quad \text{conception} \\ 0 & \text{at} \quad \text{kidding} \end{cases}$
Tl	Lactation time (days)	$\frac{dTl}{dt} = LAC$
Tp	Pregnancy time (days)	$\frac{dTp}{dt} = PREG$

Table S3 *Regulating sub-system: parameters*

Parameter	Value
k_M[1]	0.0033
GU_i[2]	0.000103
GU_a[2]	-0.00038
GU_b[2]	0.128
GU_c[2]	0.613
k_{C0C}[3]	5
k_{C0L}[3]	1
k_{CL}[3]	0.04
k_{LA}[3]	0.006
k_{GA}[3]	0.8
k_{AC0}[3]	0.007
k_{GC0}[3]	0.85

[1]Calibrated to obtain M=0.5 at t=210 days

[2]Calibration based on Koong et al. (1975)

[3]Calibrated to obtain a complete 360 days cycle of dimensionless material in C_0-C-L-A

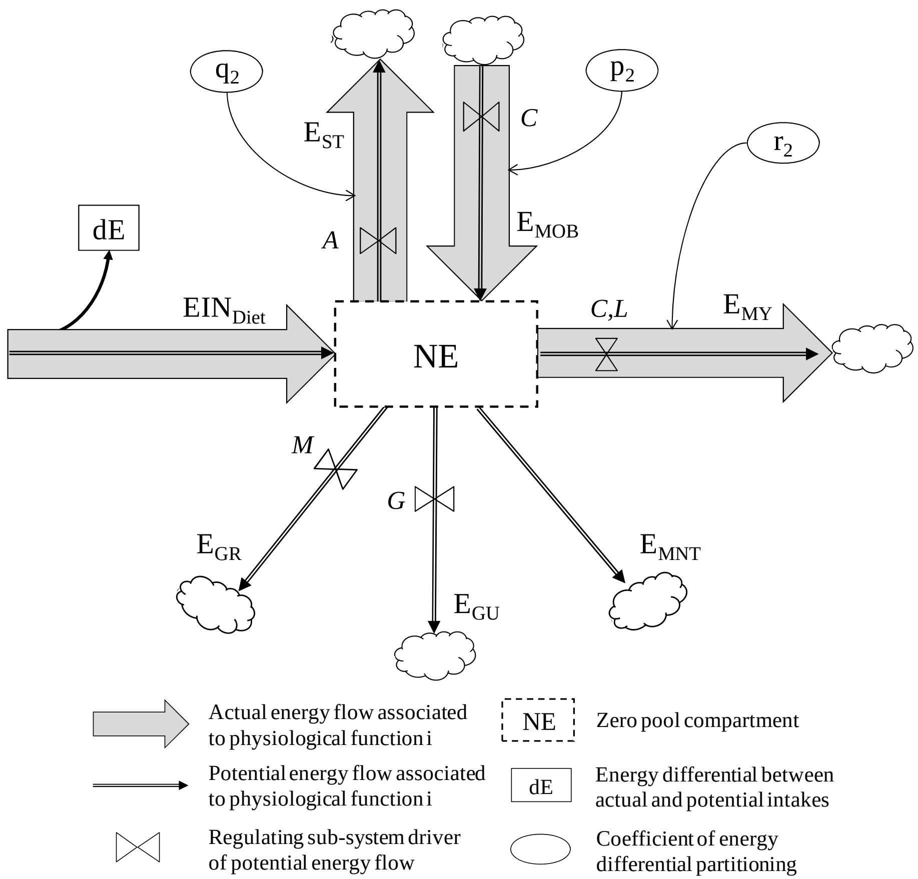
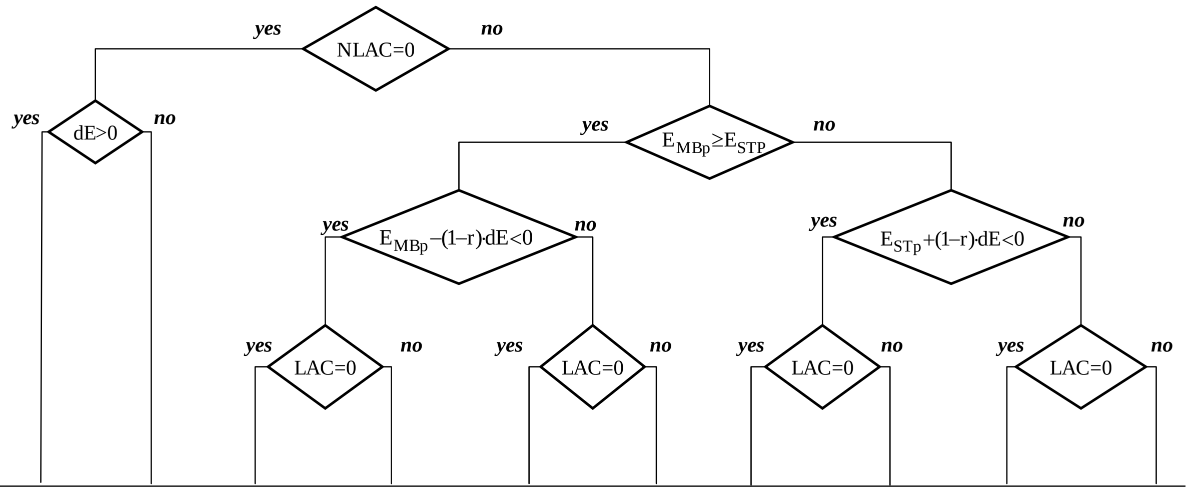


Figure S2 Energy flows of the operating sub-system of the animal model in SIGHMA. Abbreviations used: EGR = energy for growth; EGU = energy of the gravid uterus; EMNT = maintenance energy; EMY = energy exported in milk; EMOB = energy from mobilization; EST = energy for reconstitution; EINdiet = energy from diet; dE = differential of energy generated by EINdiet and Einp, potential intake of energy; NE = zero pool compartment; q2 = partitioning coefficient for reconstitution; p2 = partitioning coefficient for mobilisation; r2 = partitioning coefficient for milk energy exportation; A = theoretical hormone of anabolism; C = theoretical hormone of catabolism; L = theoretical hormone of lactation; M = theoretical hormone of growth; G = theoretical hormone of gestation.

Table S4 *Operating sub-system: physiological flows of energy*

Variable	Description	Equation
Energy flows (Mcal/d)		
E_{GR}	Growth	$E_{GR} = EV_{GR} \cdot M \cdot k_M \cdot (BW_m - BW_b) \cdot ON$
E_{GU}	Gravid uterus	$E_{GU} = EV_{GU} \cdot G(-0.1016 \cdot LS^2 + 1.0659 \cdot LS + 0.0358) \cdot ON$
E_{MNT}	Maintenance	$E_{MNT} = (0.79 + 0.01 \cdot (BW_p - 60)) \cdot EV_{ufl} \cdot ON$
E_{MBp}	Potential mobilisation	$E_{MB_p} = C \cdot EV_{MB} \cdot k_{MB} \cdot ON$
E_{STp}	Potential reconstitution	$E_{STp} = A * EV_{ST} * (k_{MB} / k_{CA}) * ON$
E_{MYp}	Potential milk exportation	$E_{MYp} = \begin{cases} ((k_{MY} \cdot C + (1-k_{MY}) \cdot L) \cdot POT \cdot 1.446 \cdot LAC \cdot NLAC_{effect} \cdot ON & \text{if } Tl \in]0, LL] \\ 0 & \text{else} \end{cases}$
E_{INp}	Potential intake	$E_{INp} = ((E_{GR} + E_{GU} + E_{MNT} + E_{STp} + E_{MYp}) - E_{MBp}) \cdot ON$
E_{MB}	Mobilisation	$E_{MB} = E_{MBp} + p_2 \cdot dE$
E_{ST}	Reconstitution	$E_{ST} = E_{STp} + q_2 \cdot dE$
E_{MY}	Milk exportation	$E_{MY} = E_{MYp} + r_2 \cdot dE$
Control		
dE	Energy differential between potential energy intake and real intake	$dE = (E_{IN_{diet}} - E_{INp}) \cdot ON$
k_{MB}	Scaling variable to link body weight dynamic and production potential	$k_{MB} = \begin{cases} 0.09317 \cdot POT - 0.02637 & \text{if } NLAC > 1 \\ 0.08944 \cdot POT - 0.02532 & \text{if } NLAC = 1 \end{cases}$
TreshDead		$ThreshDead = \begin{cases} 2.28 \cdot 10^{-5} \cdot NLAC^2 - 1.9 \cdot 10^{-4} \cdot NLAC + 5.4 \cdot 10^{-4} & \text{if } NLAC \in]0, 13[\\ 0.5 & \text{if } NLAC \geq 13 \text{ or } AGE \geq 4745 \text{ or } BW < 30 \end{cases}$
Coefficients of energy partitioning		
p	Potential mobilisation	See Figure S3
q	Potential reconstitution	See Figure S3
r	Potential milk production	See Figure S3

p_2	Mobilisation	$p_2 = \begin{cases} p \cdot Z & \text{if} \quad LAC=1 \\ p & \text{else} \end{cases}$
q_2	Reconstitution	$q_2 = \begin{cases} q \cdot X & \text{if} \quad LAC=1 \\ q & \text{else} \end{cases}$
r_2	Milk production	$r_2 = r + (1-X) \cdot q - (1-Z) \cdot p$
Theoretical function		
X	q modulation	$X = \dfrac{1}{1+\left(\dfrac{pctBR}{0.25}\right)^{30}}$
Z	p modulation	$Z = \dfrac{1}{1+\left(\dfrac{pctBR-0.3}{0.25}\right)^{30}}$



p	0	-1	$\frac{-E_{MBp}}{dE}$	$\frac{-E_{MBp}}{dE}$	-1	-0.5	$\frac{-E_{STP}}{dE}-1$	$\frac{-E_{STP}}{dE}-0.5$	0	0
q	1	0	$1+\frac{-E_{MBp}}{dE}$	$0.5+\frac{-E_{MBp}}{dE}$	0	0	$\frac{-E_{STP}}{dE}$	$\frac{-E_{STP}}{dE}$	1	0.5
r	0	0	0	0.5	0	0.5	0	0.5	0	0.5

Figure S3 Logic of determination of energy partitioning coefficients p, q and r .

Table S5 *Operating sub-system: performances*

Variable	Description	Equation	Unit
Body weight composition			
BW_p	Potential empty body weight	$\frac{dBW_p}{dt}=(BW_m-BW_b)\cdot k_M\cdot M+((\frac{A}{k_{CA}}\cdot k_{MB})-C\cdot k_{MB})$	kg/d
BW	Empty body weight	$\frac{dBW}{dt}=(BW_m-BW_b)\cdot k_M\cdot M+\frac{A\cdot k_{MB}}{k_{CA}}+\frac{q_2\cdot dE}{EV_{ST}}-C*k_{MB}-\frac{p_2\cdot dE}{EV_{MB}}$	kg/d
BR	Body reserves	$\frac{dBR}{dt}=pctBR_p\cdot(BW_m-BW_b)\cdot k_M\cdot M+(\frac{A\cdot k_{MB}}{k_{CA}})+(\frac{q_2\cdot dE}{EV_{ST}})-C\cdot k_{MB}-(\frac{p_2\cdot dE}{EV_{MB}})$	kg/d
pctBR	Proportion of body reserves	$pctBR=\frac{BR}{BW_p}$	
GU	Gravid uterus	$\frac{dGU}{dt}=G\cdot(-0.016\cdot LS^2+1.0659\cdot LS+0.0358)$	kg/d
Production			
MY_p	Potential milk yield	$MY_p=\begin{cases}L\cdot POT\cdot 1.3943\cdot LAC\cdot NLAC_{effect} & \text{if } Tl\in]0,LL]\\ 0 & \text{else}\end{cases}$	kg/d
$FCMY_p$	Potential fat corrected milk yield	$FCMY_p=\frac{E_{MY_p}}{EV_{FCMY}}$	kg/d
MY	Milk yield	$MY=MY_p+(0.428\cdot(r_2\cdot dE)^2+1.348\cdot dE+0.0016)$	kg/d
FCMY	Fat corrected milk yield	$FCMY=\frac{E_{MY}}{EV_{FCMY}}$	kg/d
WKLAC	Lactation week		
LL	Lactation length		d
NLAC	Lactation number		integer
$NLAC_{effect}$	Lactation number effect	$NLAC_{effect}=1.26\cdot e^{-0.058\cdot NLAC}-0.92\cdot e^{-0.92\cdot NLAC}$	
Energy intake			
INTCAP	Intake capacity	$INTCAP=(1.17+(BW_p-60)\cdot 0.016+0.24\cdot FCMY_p))\cdot(0.5+0.5\cdot(1-e^{-0.6\cdot WKLAC})$	UE/d
QD_i	Distributed quantity of feedstuff i	Diet input determined by feeding management	kg of DM/d

QI_i	Intake of feedstuff i	$QI_i = \begin{cases} 0.5 \cdot INTCAP / UE_i & if\ i = F1\ or\ i = F2 \\ \max(0, (INTCAP - \sum_i QD_i \cdot UE_i) / UE_{F3} & if\ i = F3 \\ QD_i & if\ i = C \end{cases}$	kg of DM/d
UE_i	Fill unit of feedstuff i	$UE_i = \begin{cases} QI_C \cdot 0.38 \cdot UE_{F3} & \text{if } i=C \\ \text{input diet file} & \text{else} \end{cases}$	UE/kg DM
UF_i	Energy value of feedstuff i	UFi=input diet file	UFL/kg of DM
E_{diet}	Energy ingested from diet	$E_{diet} = (QI_{F1} \cdot UF_{F1} + QI_{F2} \cdot UF_{F2} + QI_{F3} \cdot UF_{F3} + QD_C \cdot UF_C) \cdot EV_{UFL}$	Mcal/d
E_{MAJ}	Energy majoration due to digestive interactions	$E_{MAJ} = 2.5 \cdot (\frac{FCMY_p}{BW_p}) \cdot EV_{UFL}$	Mcal/d
EIN_{diet}	Available energy from diet	$EIN_{diet} = E_{diet} - E_{MAJ}$	Mcal/d

Table S6 *Operating sub-system: parameters*

	Value	Unit
Energy conversion		
EV_{GU}	0.78[1]	Mcal /kg gravid uterus
EV_{GR}	3.31[2]	Mcal /kg body weight
EV_{MB}	4.42[3]	Mcal /kg body weight
EV_{ST}	6.60[4]	Mcal /kg body weight
EV_{FCMY}	0.67[4]	Mcal /kg fat corrected milk yield
EV_{UFL}	1.70[4]	Mcal /UFL
Scaling regulating sub-system dynamics		
kCA		
kMY	0.45	
Input settings		
BW_b	User defined	kg
BW_m	User defined	kg
POT	User defined	kg
LS	2	integer
$pctBR_p$	0.2	kg/kg

[1]Martin et Sauvant, 2009.
[2]Luo, 2004.
[3]Sauvant, unpublished data.
[4]INRA, 2007.

Table S7 *Operating sub-system: connection with management sub-model*

Variable	Description	Event actions
Control		
ExtLac	Extended lactation status	$ExtLAC = \begin{cases} 1 \ at \ \text{NonPreg Management event} \textit{depending on N}\text{PregOption} \\ 0 else \end{cases}$
NumGoat	Individual number	$NumGoat = \text{i at birth}$
ME	Management entity number	Birth, death, replacement integration, non-pregnant management, voluntary culling
MG	Mating group number	$MG = i$ at $Mating$ group formation event with $\text{i} \in [1,3]$
Date		
DAT_{CON}	Conception	$\text{DAT}_{\text{CON}} = \text{t during Mating event}$
DAT_{NXTKID}	Next kidding	$DAT_{NXTKID} = \begin{cases} DAT_{CON} + 150 at \text{Pr} egnancy\ diagnosis\ event \\ 0 \quad at \quad Kidding \end{cases}$
DAT_{PRVKID}	Previous kidding	$\text{DAT}_{\text{PRVKID}} = \begin{cases} \text{DAT}_{\text{NXTKID}} \ \text{at Kidding} \\ 0 \quad \text{else} \end{cases}$
DAT_{DRY}	Drying off	$\text{DAT}_{\text{DRY}} = \begin{cases} \text{DAT}_{\text{NXTKID}} - 60 \ \text{at Drying Management event} \\ 0 \quad \text{at} \quad \text{Drying} \end{cases}$