Animal journal

Coupling a reproductive function model to a productive function model to simulate lifetime performance in dairy cows

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Supplementary materials

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Table S1 Dairy cow Reproductive Function Model (RFM): differential system (see Table S2 for variables and flows definitions)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Abbreviation | Variable | Differential equation | | | | | | | | | | | | Initial |
|  |  | | | | | | | | | | | | |  |
| Competence *stage* | | | | | | | | | | | | | | |
| PRPB | Prepubertal | −r0 |  |  |  |  |  |  |  |  |  |  |  | 0.999 |
| ANST | Anestrous | +r0 | −r1 |  |  |  |  | +r6a | +r6b | +r6c |  | −r8 |  | 0.001 |
| PREO | Pre-ovulating |  | +r1 | −r2 |  |  |  |  |  |  |  |  |  | 0.000 |
| OVUL | Ovulating |  |  | +r2 | −r3 |  |  |  |  |  |  |  |  | 0.000 |
| PSTO | Post-ovulating |  |  |  | +r3 | −r4 |  |  |  | −r6c |  |  |  | 0.000 |
| LUTZ | Luteinizing |  |  |  |  | +r4 | −r5 |  | −r6b |  |  |  |  | 0.000 |
| LUTL | Luteal |  |  |  |  |  | +r5 | −r6a |  |  | −r7 |  | +r9 | 0.000 |
| GEST | Gestating |  |  |  |  |  |  |  |  |  | +r7 |  |  | 0.000 |
| ANOV | Anovulatory |  |  |  |  |  |  |  |  |  |  | +r8 | −r9 | 0.000 |
|  |  |  | | | | | | | | | | | |  |
| Hormonal signal | | | | | | | | | | | | | | |
| E2 | Estradiol | ωE2[1]·[OVU+0.3∙PREO+0.1∙(ANST+PSTO+LUTZ+LUTL+GEST) - Clearance·ωE2[2]·E2] | | | | | | | | | | | | 0.200 |
| P4 | Progesterone | ωP4[1]·[LUTL+GEST - ωP4[2]·P4 ] | | | | | | | | | | | | 0.100 |
|  |  | | | | | | | | | | | | |  |
| Physiological *time* | | | | | | | | | | | | | | |
| dip1 | Days in pregnancy | 1·pregnancy | | | | | | | | | | | | 0.000 |

1 dip is reset to zero by events parturition and death (of embryo or fetus)

Table S2 Dairy cow Reproductive Function Model (RFM): variables and flows (see Table S1 for differential system definition)

|  |  |  |
| --- | --- | --- |
| Equation | Definition | Unit1 |
| Variable derived from GARUNS2 |  |  |
| EB= I−(M+Y+P+AW)+150 | Net Energy Balance | MJ ME/d |
| EB\*=EB+150 | transformed net Energy Balance | MJ ME/d |
| TPEW=(I+CX)/W | Total Processed Energy per Weight | MJ ME/d/kg |
| Boolean variable of physiological status |  |  |
| pregnancy=1 if pregnant; 0 if not | Pregnancy status indicator | du |
| Regulation variable |  |  |
| cyclicity=(EB\*)50/[(EB\*)50+(B+150)50] | Control of cyclicity resumption | du |
| ovulation=1−ANST50/(ANST50+0.0150) | Control of ovulation induction | du |
| luteolysis=1−PSTO50/(PSTO50+0.00150) | Control of luteolysis induction | du |
| impregnation=P410/(P410+0.410) | Control of estrous intensity | du |
| clearance=1+0.4·TPEW50/(TPEW50+0.550) | Control of estradiol clearance | du |
| fertilization=0.3·PREO+OVUL+0.1·PSTO | Control of fertilization potential | du |
| survival | Control of embryonic/fetal death | du |
| = M1 if dip<16 |  |  |
| = M2 if dip∈ [16; 45] |  |  |
| = M3 if dip>45 |  |  |
| Random variable3 |  |  |
| fertility ~ U[0 ; fertilization] | Probability of conception | du |
| mortality ~ U[0 ; 1] | Probability of embryonic/fetal death | du |
| Transition flows between competence stages |  |  |
| r0 = νB∙k0∙PRPB∙ANST | Prepubertal to Anestrous | d-1 |
| r1 = νZ∙k1∙cyclicity∙ANST | Anestrous to Pre-ovulating | d-1 |
| r2 = νZ∙k2∙ovulation∙PREO | Pre-ovulating to Ovulating | d-1 |
| r3 = νZ∙k3∙OVUL | Ovulating to Post-ovulating | d-1 |
| r4 = νZ∙k4∙PSTO | Post-ovulating to Luteinizing | d-1 |
| r5 = νZ∙k5∙LUTZ | Luteinizing to Luteal | d-1 |
| r6a= νZ∙k6∙luteolysis∙LUTL | Luteal to Anestrous | d-1 |
| r6b= νZ∙k6∙luteolysis∙LUTZ | Luteinizing to Anestrous | d-1 |
| r6c= νZ∙k6∙luteolysis∙PSTO | Post-ovulating to Anestrous | d-1 |
| r7 = νZ∙k7∙pregnancy∙LUTL∙GEST | Luteal to Gestating | d-1 |
| r8 = νZ∙k8∙ANST | Anestrous to Anovulatory | d-1 |
| r9 = νZ∙k9∙impregnation∙ANOV | Anovulatory to Luteal | d-1 |
| Event time4 |  |  |
| tovulation | Time of ovulation | d |
| tinsemination | Time of insemination | d |
| tconception | Time of conception | d |
| tdeath | Time of embryo/fetus death | d |
| tparturition | Time of parturition | d |

1 ME: metabolizable energy; du: dimensionless unit

2 Use of metabolizable energy flows from GARUNS model: I: intake, M: maintenance, Y: milk yield, P: pregnancy, AW: anabolism of non-labile body mass W, CX: catabolism of labile body mass X

3 Random numbers are drawn in U[m ;M]: Uniform distribution between m and M

4 Times are recorded for each successive events

Table S3 Dairy cow Reproductive Function model (RFM): events (see Table S1 for differential system definition)

|  |  |  |
| --- | --- | --- |
| Event | Trigger condition | Action1 |
| Ovulation | OVUL=max(PRPB;ANST;PREO;  OVUL;PSTO;LUTZ;  LUTL;GEST;ANOV) | tovulation = t |
| Insemination | Estrous detected  t > 450  pregnancy = 0 | tinsemination = t  tconception = t + 1 |
| Conception | t = tconception  pregnancy = 0  fertility > νI | OVUL = OVUL − 0.001  GEST = GEST + 0.001  tconception = t  pregnancy = 1 |
| Parturition | t = tparturition | LUTL = LUTL + GEST  GEST = 0  tparturition = t  pregnancy = 0  dip = 0 |
| Abortion | mortality > 1 − e - survival⋅dt | LUTL = LUTL + GEST  GEST = 0  tdeath = t  pregnancy = 0  dip = 0 |

1 t: simulation time = age of the individual cow

Table S4 Dairy cow Reproductive Function Model (RFM): parameters

|  |  |  |
| --- | --- | --- |
| Symbol | Unit | Value |
| Genetic-scaling parameter1 |  |  |
| νB | - | 1.700 |
| νZ | - | 1.000 |
| νI | - | 0.020 |
| Fractional rate |  |  |
| k0 | d-1 | 1.000 |
| k1 | d-1 | 4.555 |
| k2 | d-1 | 4.513 |
| k3 | d-1 | 1.093 |
| k4 | d-1 | 0.417 |
| k5 | d-1 | 0.210 |
| k6 | d-1 | 1.233 |
| k7 | d-1 | 4.500 |
| k8 | d-1 | 0.050 |
| k9 | d-1 | 0.240 |
| Signal release and clearance |  |  |
| ωE2[1] | - | 3.573 |
| ωE2[2] | - | 0.588 |
| ωP4[1] | - | 0.714 |
| ωP4[2] | - | 0.923 |
| Embryo and fetus mortality thresholds |  |  |
| M1 | probability | 0.0230 |
| M2 | probability | 0.0096 |
| M3 | probability | 0.0004 |
| Energy balance threshold |  |  |
| B | MJ ME2/d | -10 |

1 Standard values (mean of random distributions; see Table S5)

2 ME: metabolizable energy

Table S5 Random distributions of genetic-scaling parameters of the dairy cow productive function model (GARUNS) and reproductive function model (RFM)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | Random1  N (μ, σ) | |  |
| Symbol | Definition | Unit | Range2 | μ | σ | Proxy for |
| GARUNS | |  |  |  |  |  |
| WM | mature non labile body mass | kg | [200-800] | 450 | 25 | Format |
| νM | target labile:non-labile mass ratio | [0-1] | [0.1-0.6] | 0.33 | 0.03 | Body fatness |
| b0 | reserves storage rate | d-1 | [0.8-2.4] | 1.6 | 0.2 | Reserve lability |
| νX | labile body mass mobilization index | - | [0.2-1.8] | 1.0 | 0.1 | Maternal reserve investment in reproduction |
| νY | milk yield index | - | [0.2-1.8] | 1.0 | 0.1 | Milk potential |
| νF | milk fat secretion index | - | [0.5-1.5] | 1.00 | 0.02 | Milk fat content |
| νP | milk protein secretion index | - | [0.5-1.5] | 1.00 | 0.02 | Milk protein content |
| eD\* | optimal3 diet energy content | MJ.kg DM-1 | [9.0-15.0] | 12.3 | 0.5 | Intake capacity |
| RFM |  |  |  |  |  |  |
| νI | fertilization probability threshold | - | [0.0-0.2] | 0.026 | 0.007 | Fertility |
| νB | puberty index | - | [1.2-2.2] | 1.70 | 0.25 | Age at 1st ovulation |
| νZ | follicular dynamics rate | - | [0.9-1.1] | 1.00 | 0.05 | Estrous duration |

1 Variability for a Holstein cow

2 Cattle theoretical calculable range

3 Diet energy content maximizing intake and covering energy requirement

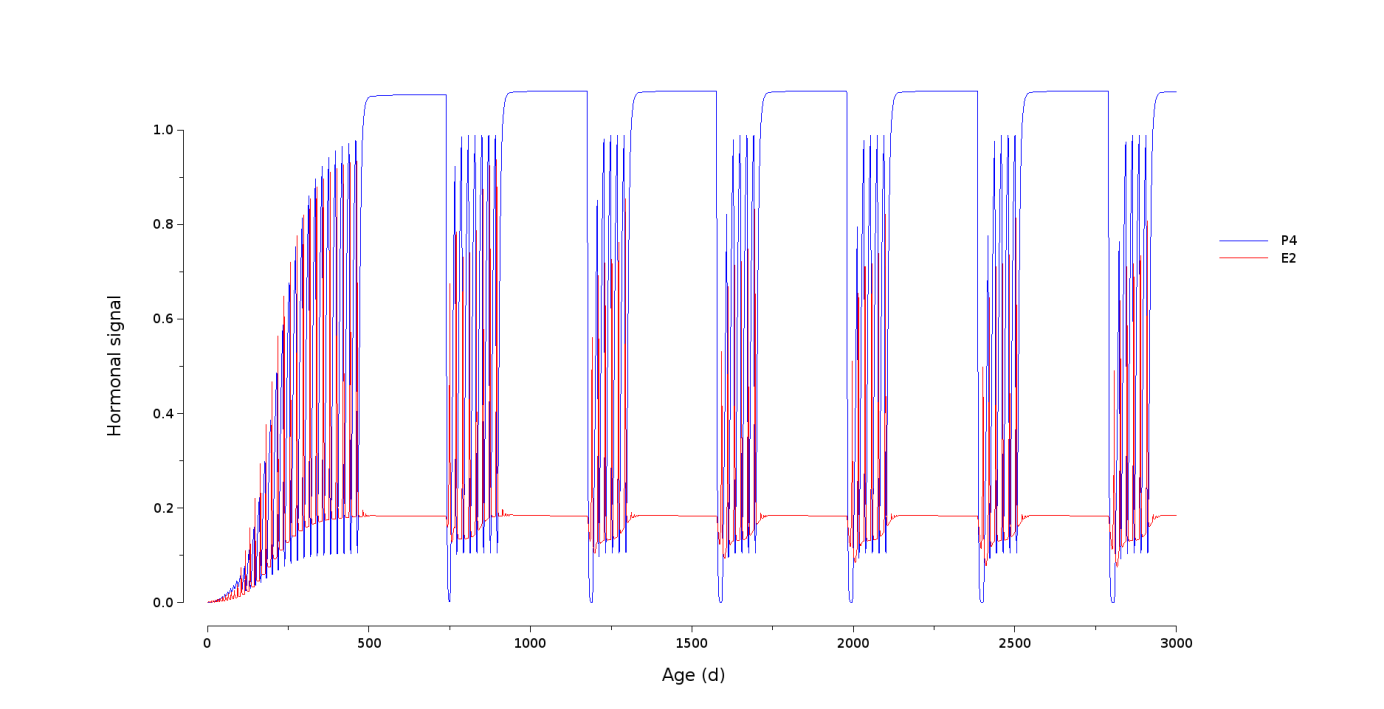
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Figure S1 Model simulation: dynamics of progesterone (P4) and estradiol (E2) over 3000d lifetime of an individual dairy cow.

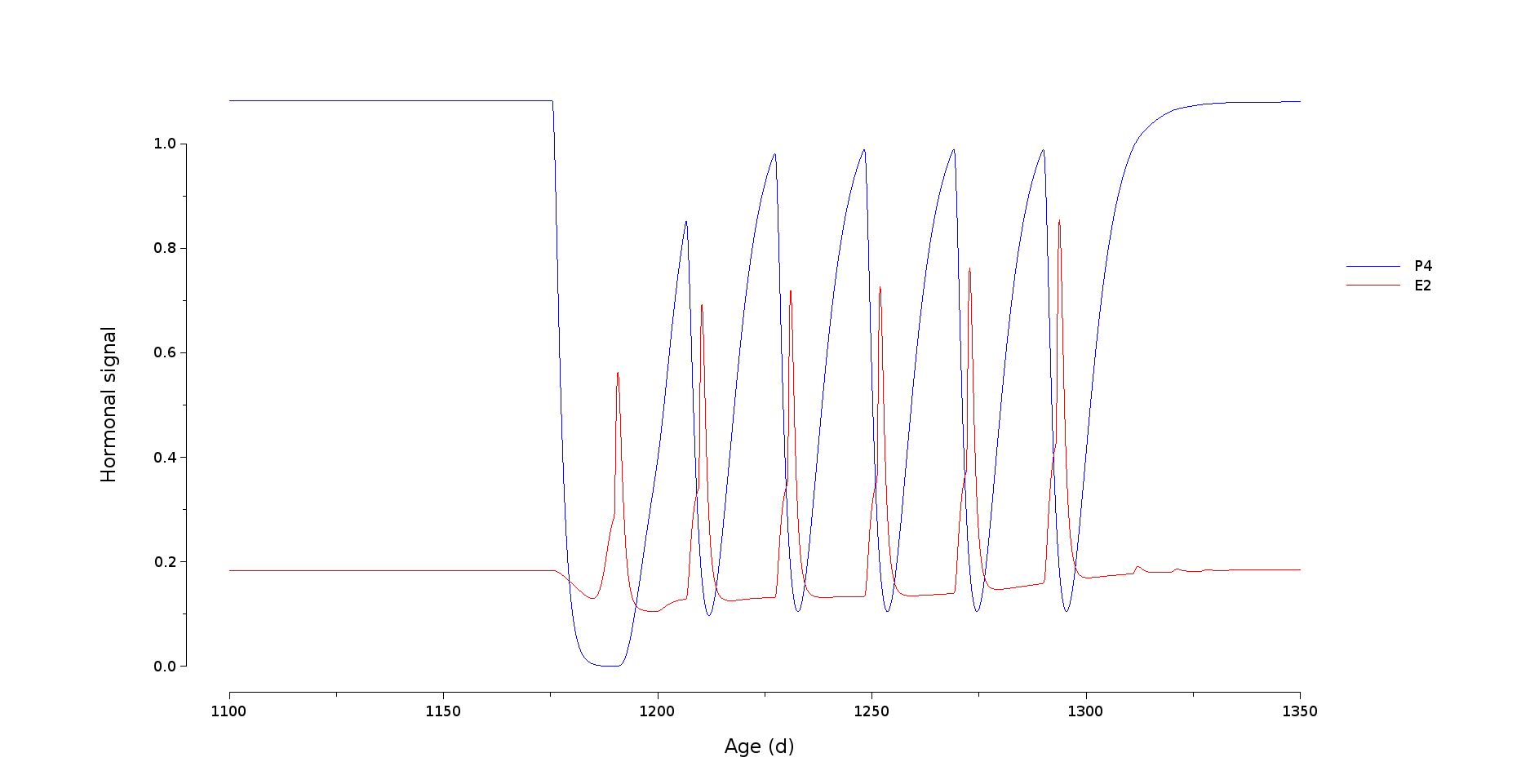
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Figure S2 Model simulation: dynamics of progesterone (P4) and estradiol (E2) over 250d between the 2nd and 3rd gestations of an individual dairy cow.

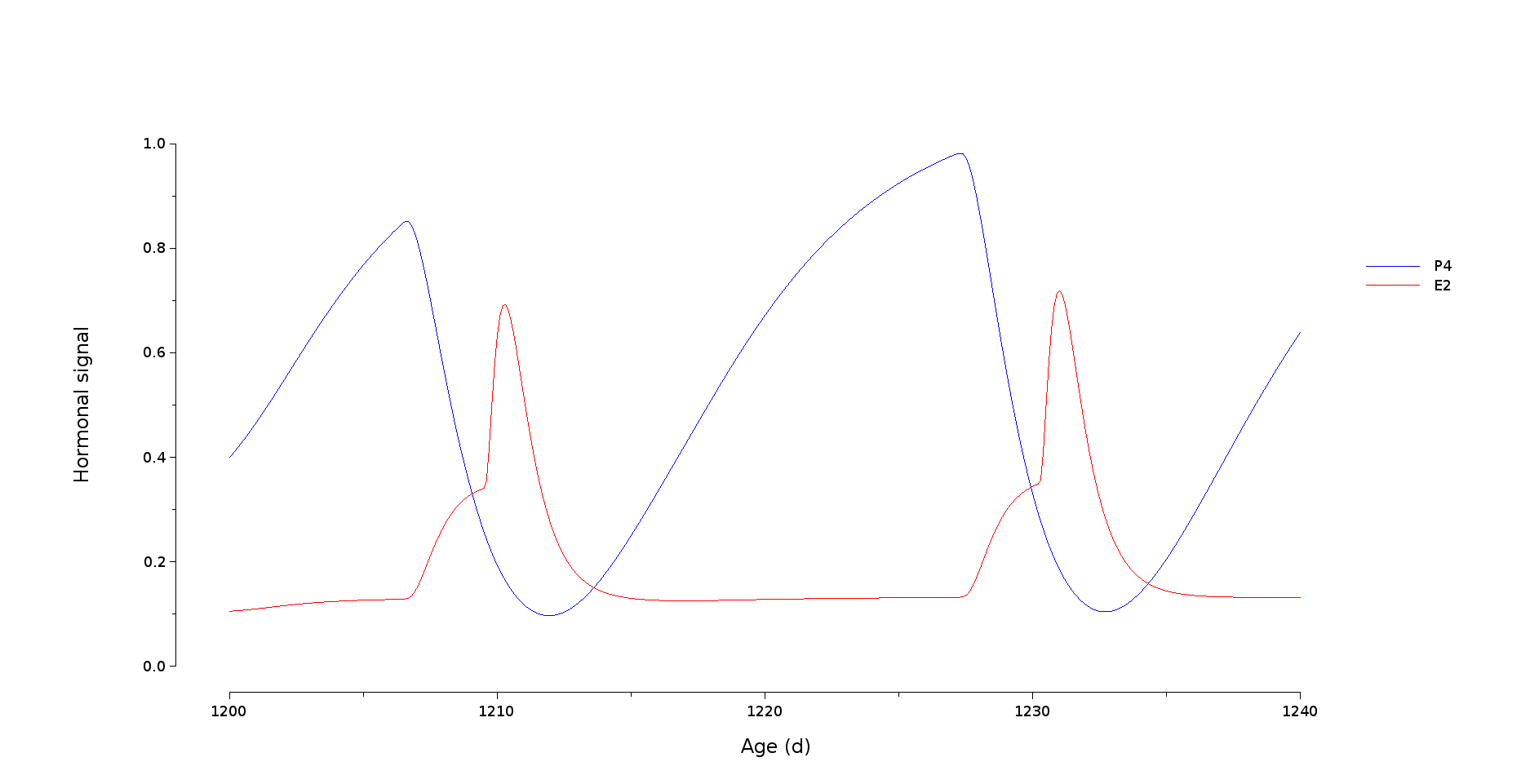
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Figure S3 Model simulation: dynamics of progesterone (P4) and estradiol (E2) over 40 days around one estrous cycle of an individual dairy cow.

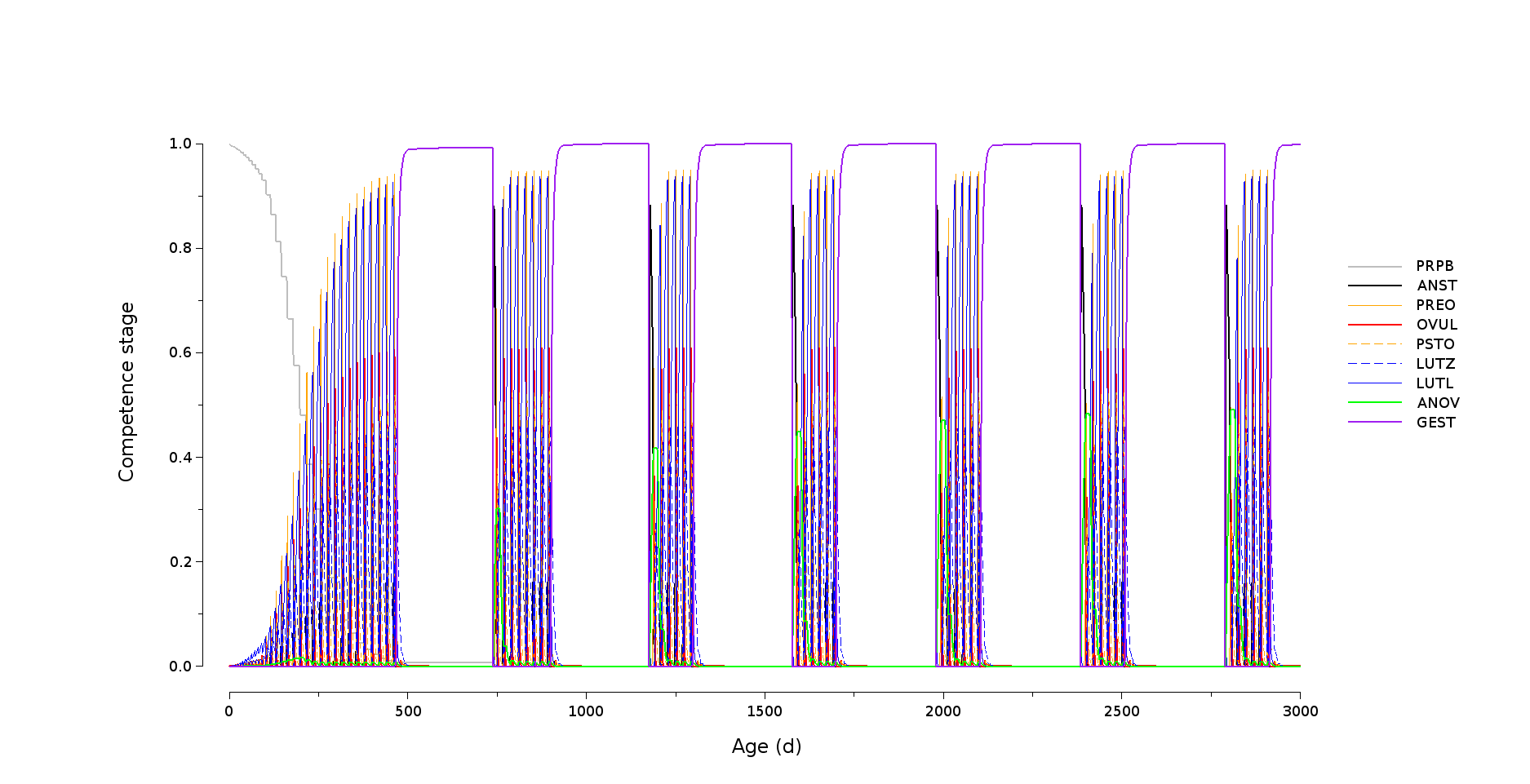


Figure S4 Model simulation: dynamics of competence stages (PRPB: prepubertal, ANST: anestrous, PREO: pre-ovulating, OVUL: ovulating, PSTO: post-ovulating, LUTZ: luteinizing, LUTL: luteal, ANOV: anovulatory, GEST: gestant) over 3000d lifetime of an individual dairy cow.

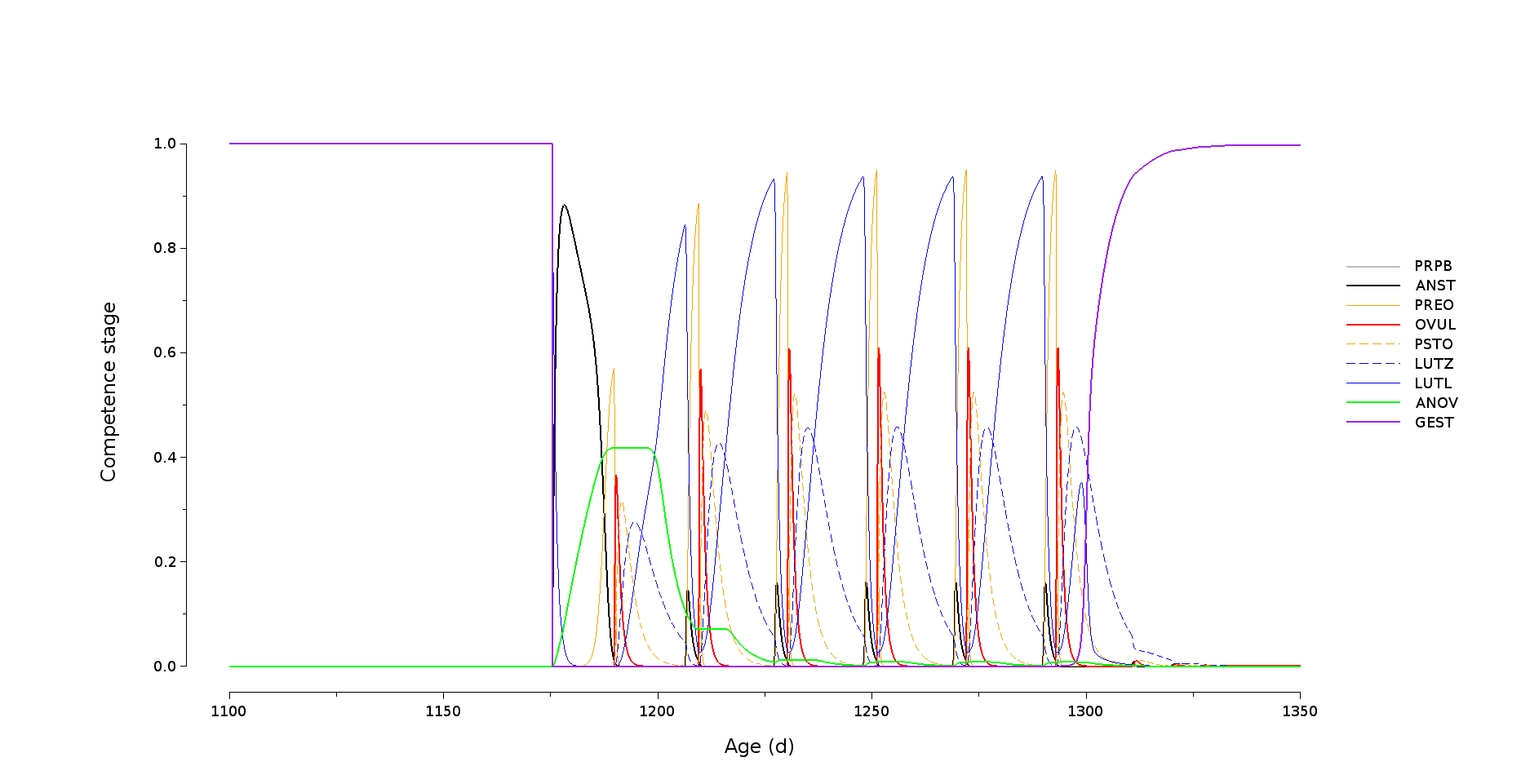


Figure S5 Model simulation: dynamics of competence stages (PRPB: prepubertal, ANST: anestrous, PREO: pre-ovulating, OVUL: ovulating, PSTO: post-ovulating, LUTZ: luteinizing, LUTL: luteal, ANOV: anovulatory, GEST: gestant) over 250d between the 2nd and 3rd gestations of an individual dairy cow.

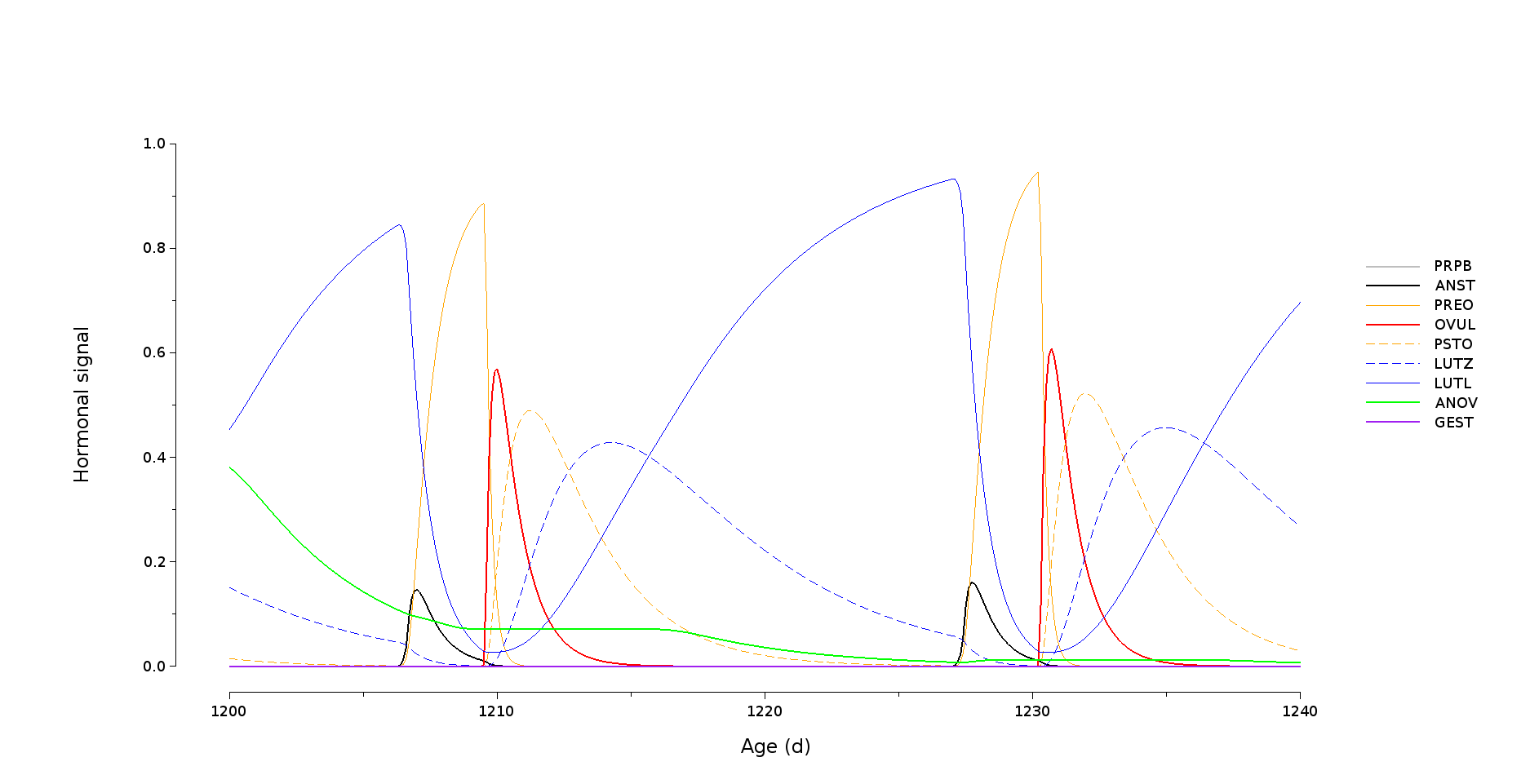


Figure S6. Model simulation: dynamics of competence stages (PRPB: prepubertal, ANST: anestrous, PREO: pre-ovulating, OVUL: ovulating, PSTO: post-ovulating, LUTZ: luteinizing, LUTL: luteal, ANOV: anovulatory, GEST: gestant) over 40 days around one estrous cycle of an individual dairy cow.



Figure S7 Model simulation: dynamics of the regulation variable fertilization (defined as a linear combination of competence stages PREO: pre-ovulating, OVUL: ovulating, and PSTO: post-ovulating) and of the random variable fertility (corresponding to the probability of conception and drawn in an uniform law with minimum zero and maximum fertilization) around ovulation (P4: progesterone and E2: estradiol shown for physiological time reference of an individual dairy cow).

An insemination at a time t within this so-called “fertility windows” leads to conception at time t + 24 hours if *fertility* > , where is a genetic-scaling parameter representing the fertilization probability threshold of an individual cow.

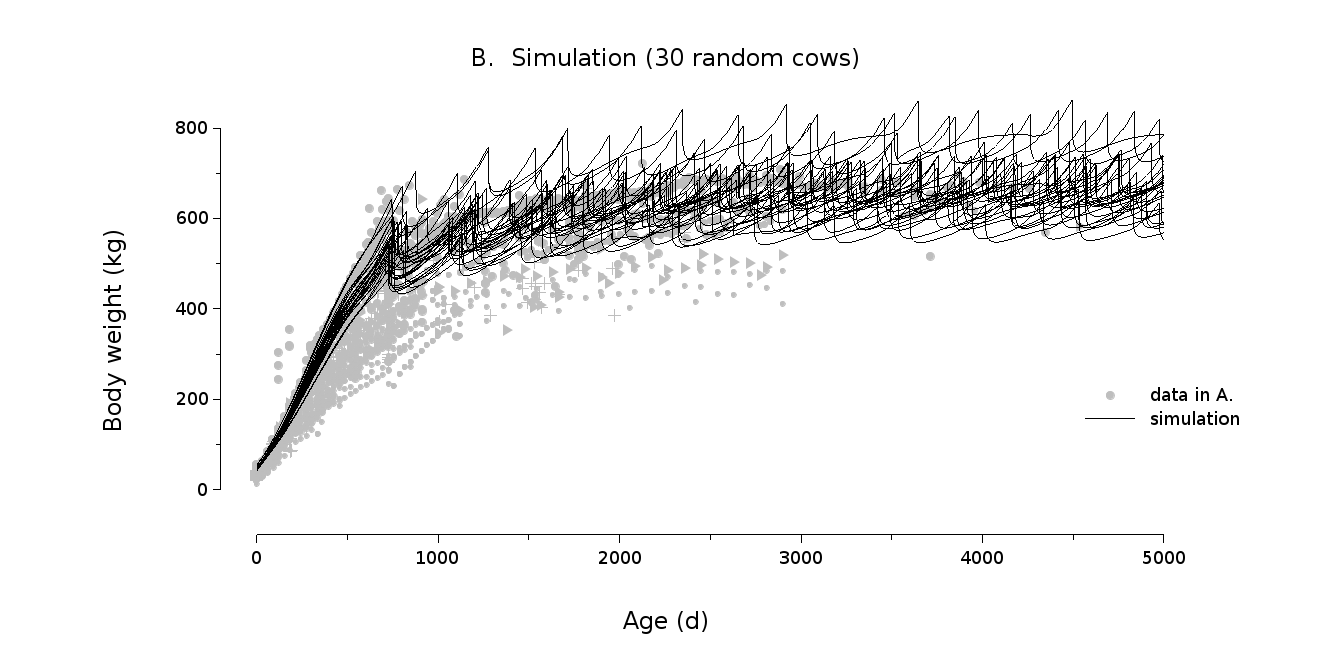
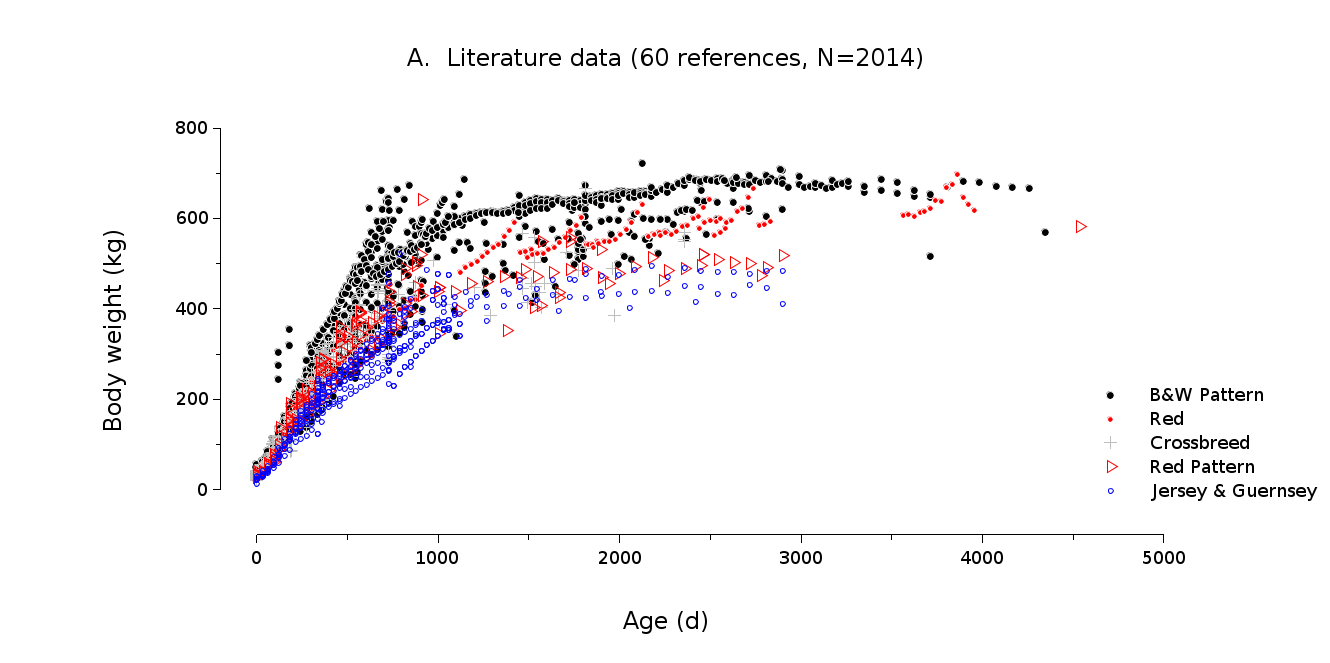
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Figure S8 Growth in Body Weight (kg) with age (days). A: literature data in dairy cattle (60 references[[1]](#footnote-1)). B: Model simulation over 5000d lifetime for 30 random individual cows.

Comment on Fig. S8: The model is relevant to simulate growth in Holstein cows.

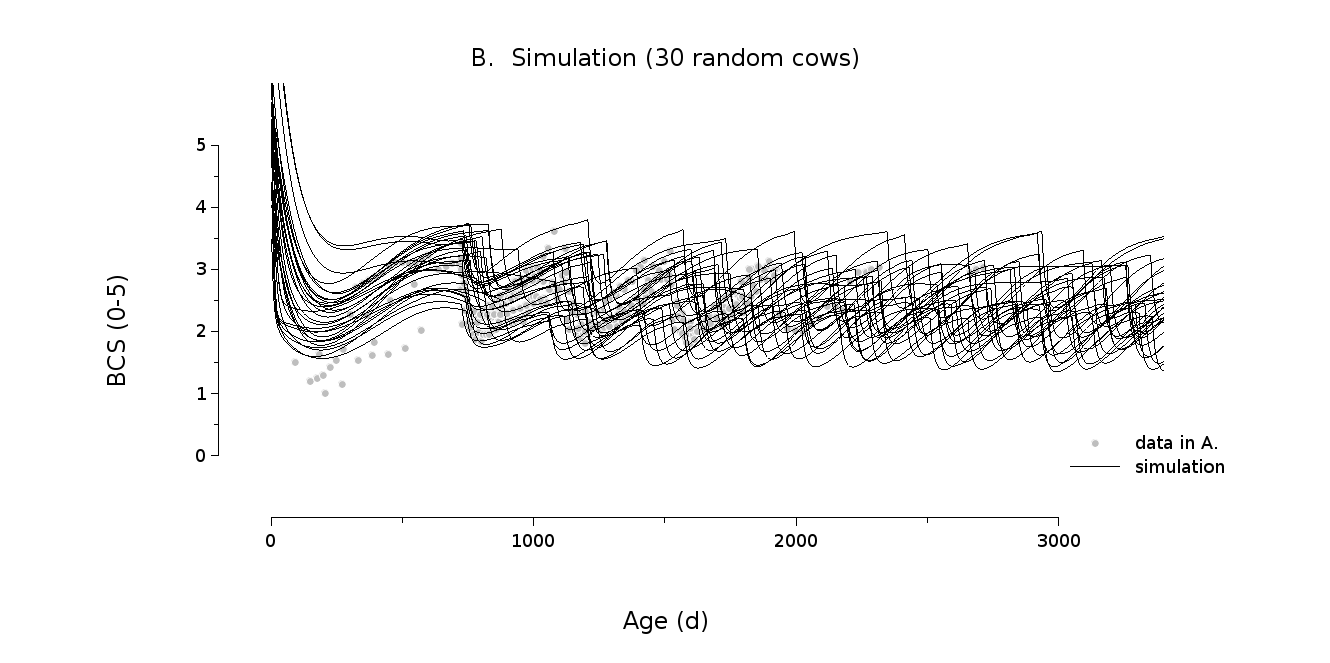
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Figure S9 Changes in Body Condition Score (BCS, [0-5]) with age (days). A: literature data in dairy cattle (10 references[[2]](#footnote-2)). B: Model simulation over 5000d lifetime for 30 random individual cows.

Comment on Fig. S9. The model provides realistic simulations of BCS except in early stage of life since the formula used to compute BCS has not been specifically validated for young stock.

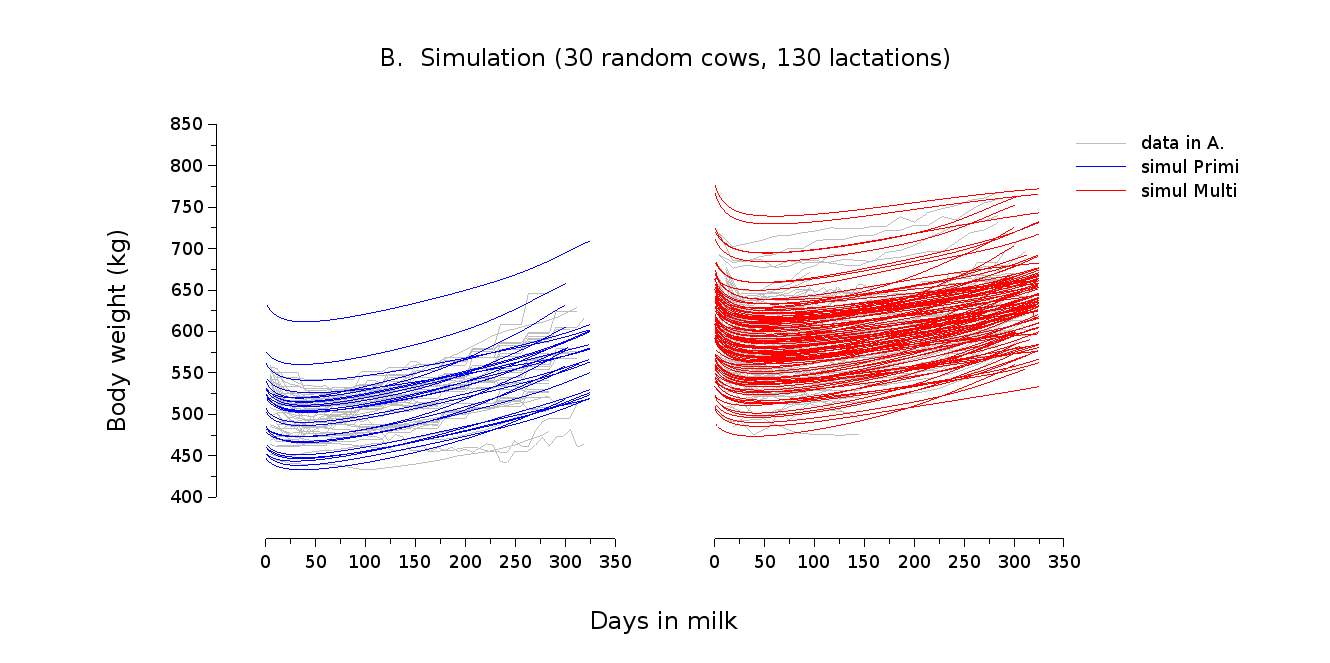
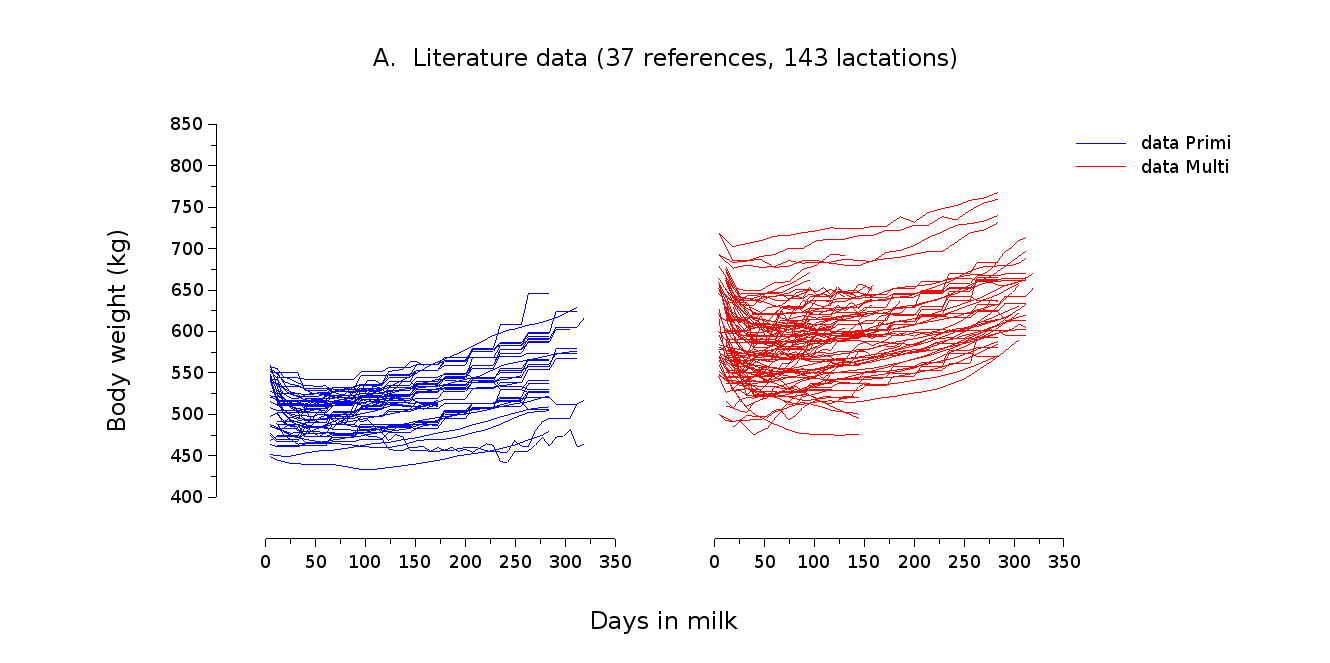
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Figure S10 Body Weight (kg) dynamics over lactation according to parity. A: literature data in dairy cattle (37 references[[3]](#footnote-3)). B:Model simulation over 320 days in milk for 30 random individual cows from parity 1 to 5 (130 lactations).

Comment on Figure S10. Model simulations of BW over lactation are consistent with literature data.

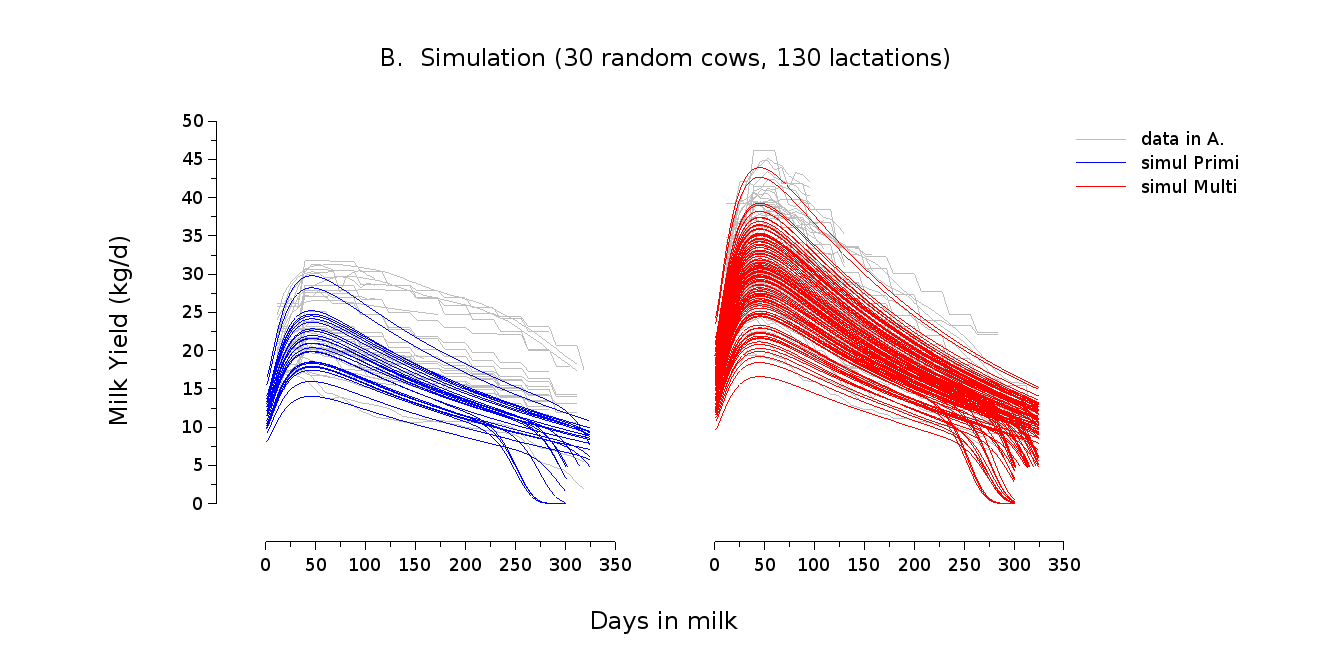
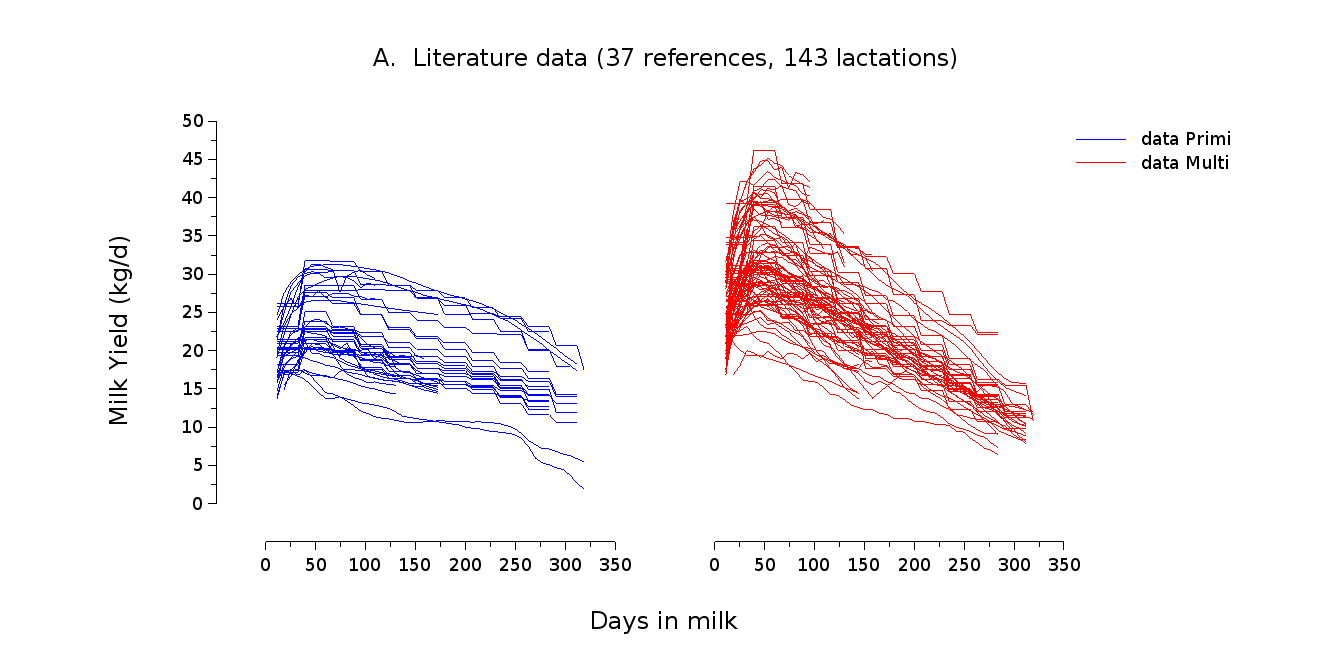
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Figure S11 Milk Yield (MY, kg/d) dynamics over lactation according to parity. A: literature data in dairy cattle (37 references[[4]](#footnote-4)). B: Model simulation over 320 days in milk for 30 random individual cows from parity 1 to 5 (130 lactations).

Comment on Figure S11. Model simulations of MY over lactation are globally consistent with literature data, but the model underestimates MY in primiparous cows.

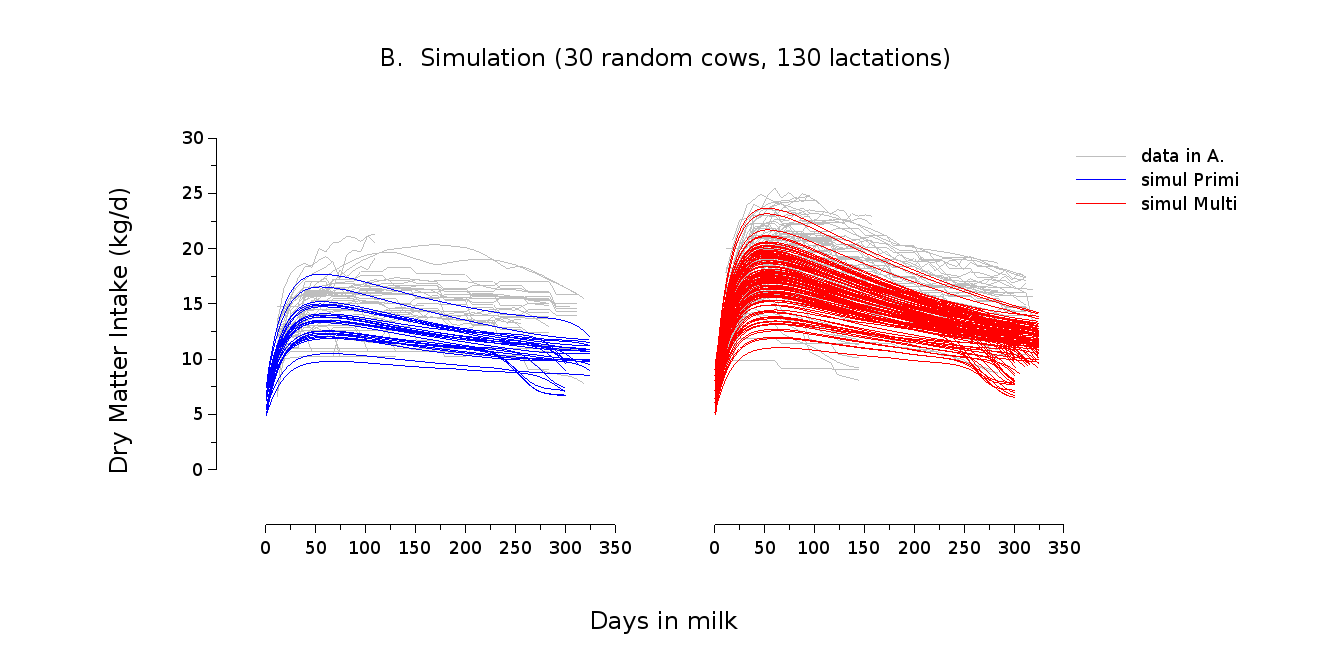
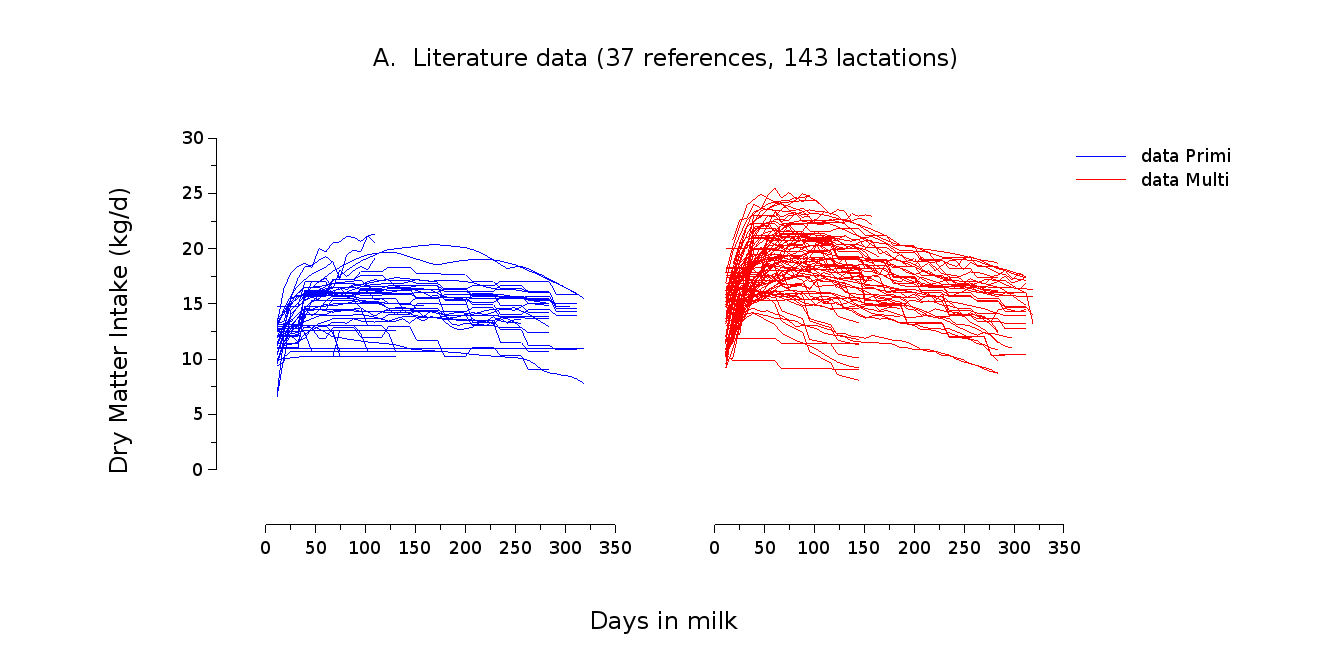
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Figure S12 Dry Matter Intake (DMI, kg/d) dynamics over lactation according to parity. A: literature data in dairy cattle (37 references[[5]](#footnote-5)). B: Model simulation over 320 days in milk for 30 random individual cows from parity 1 to 5 (130 lactations).

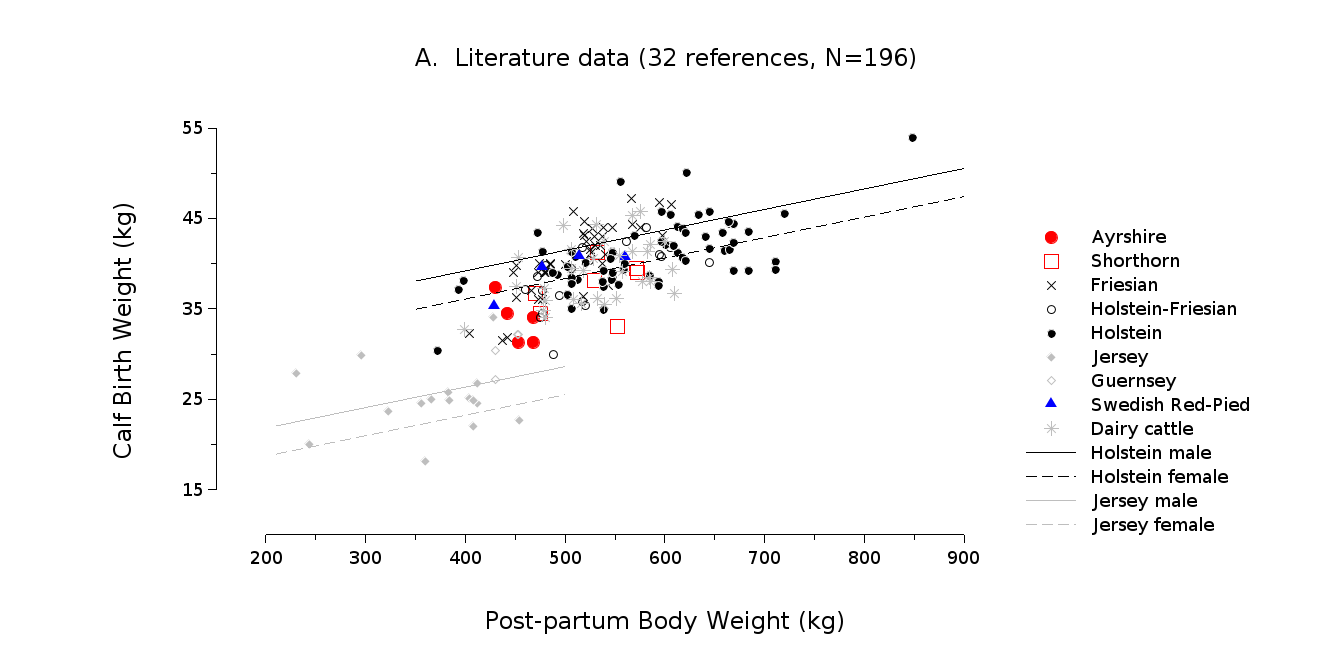
Comment on Figure S12. The model underestimates DMI in primiparous cows, which is consistent with the underestimation of MY. Globally, the model slightly underestimates DMI which is consistent with the lower diet energy content in literature data (eD=11.3 MJ/kg DM) compared to simulations (eD=12.3 MJ/kg DM).

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Figure S13 Fetal growth during gestation. A: literature data in dairy cattle (27 references[[6]](#footnote-6)). B: Model simulation for 30 random individual cows performing 296 gestations over 5000d-lifetime.

Comment on Figure S13. Model simulations of fetal growth are consistent with literature data.

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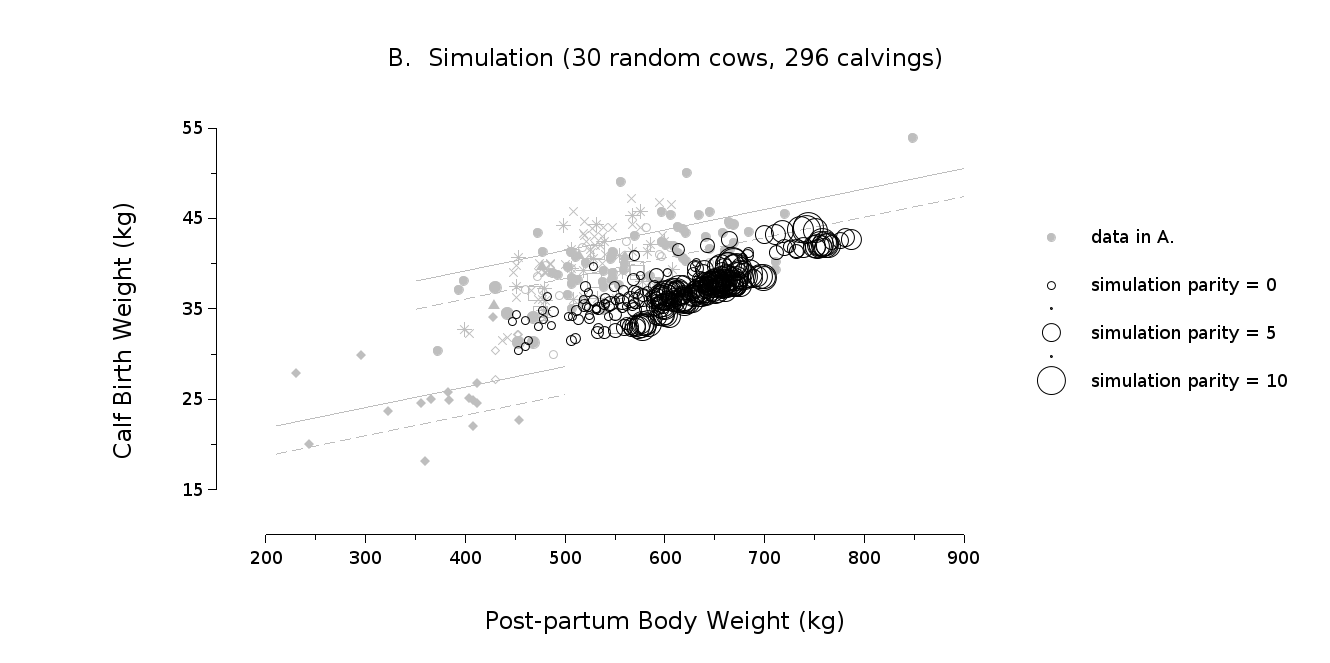
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Figure S14 Relationship between Calf Birth Weight (kg) and Post-Partum BW (kg). A: literature data in dairy cattle (32 references[[7]](#footnote-7)). B: Model simulation for 30 random individual cows performing 296 calvings over 5000d-lifetime.

Comment on Figure S14. The model slightly underestimates calf birth weight.

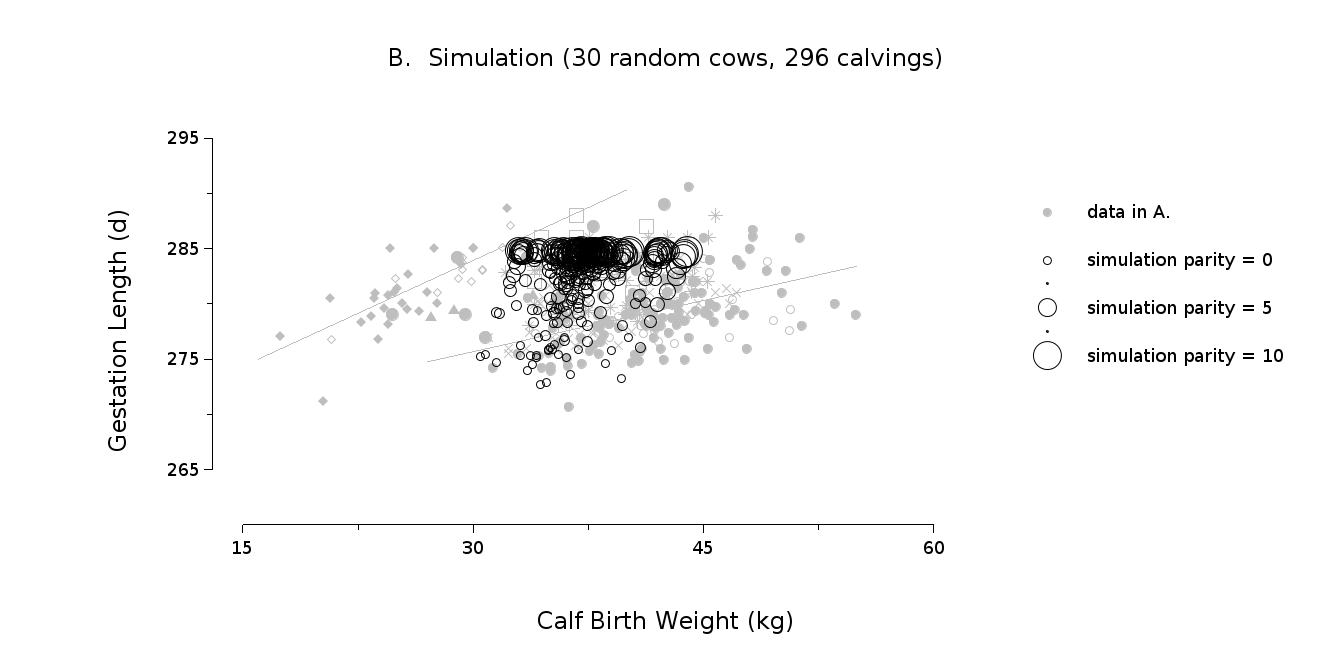
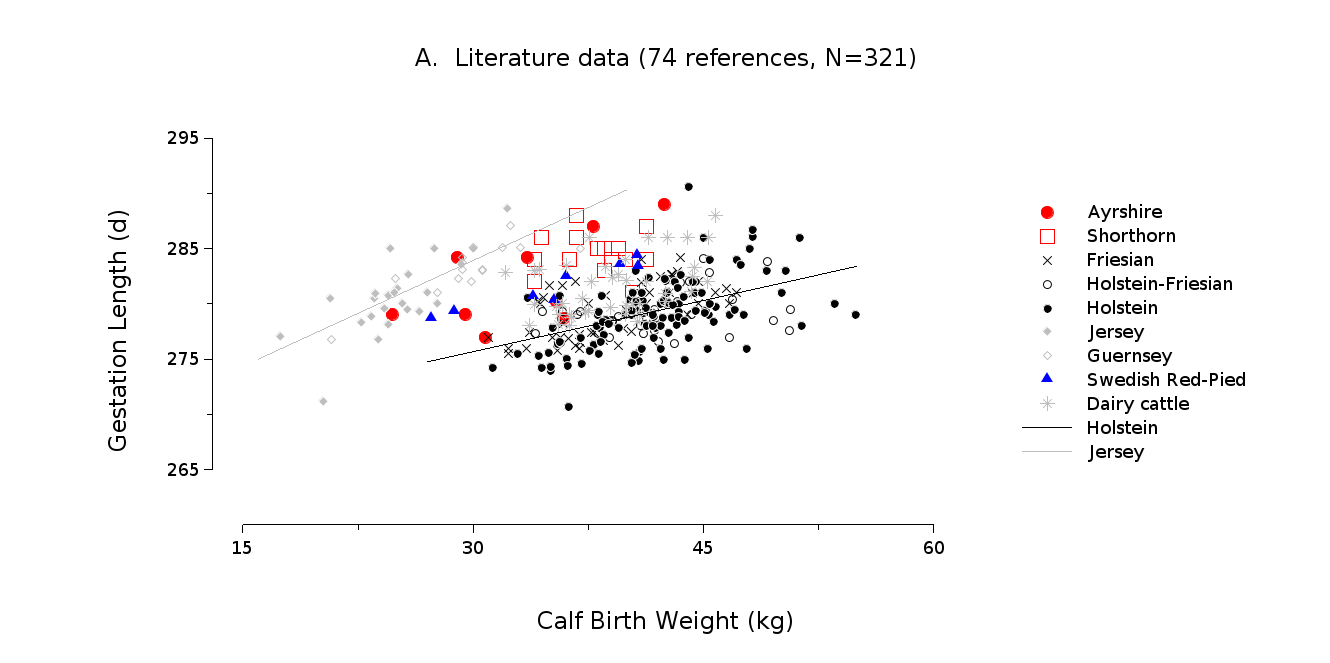
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Figure S15 Relationship between Gestation Length (d) and Calf Birth Weight (kg). A: literature data in dairy cattle (74 references[[8]](#footnote-8)). B: Model simulation for 30 random individual cows performing 296 calvings over 5000d-lifetime.

Comment on Figure S15. Model simulations are in the range of literature data (Gestation lengths are limited to a theoretical value of 285 days in the model).

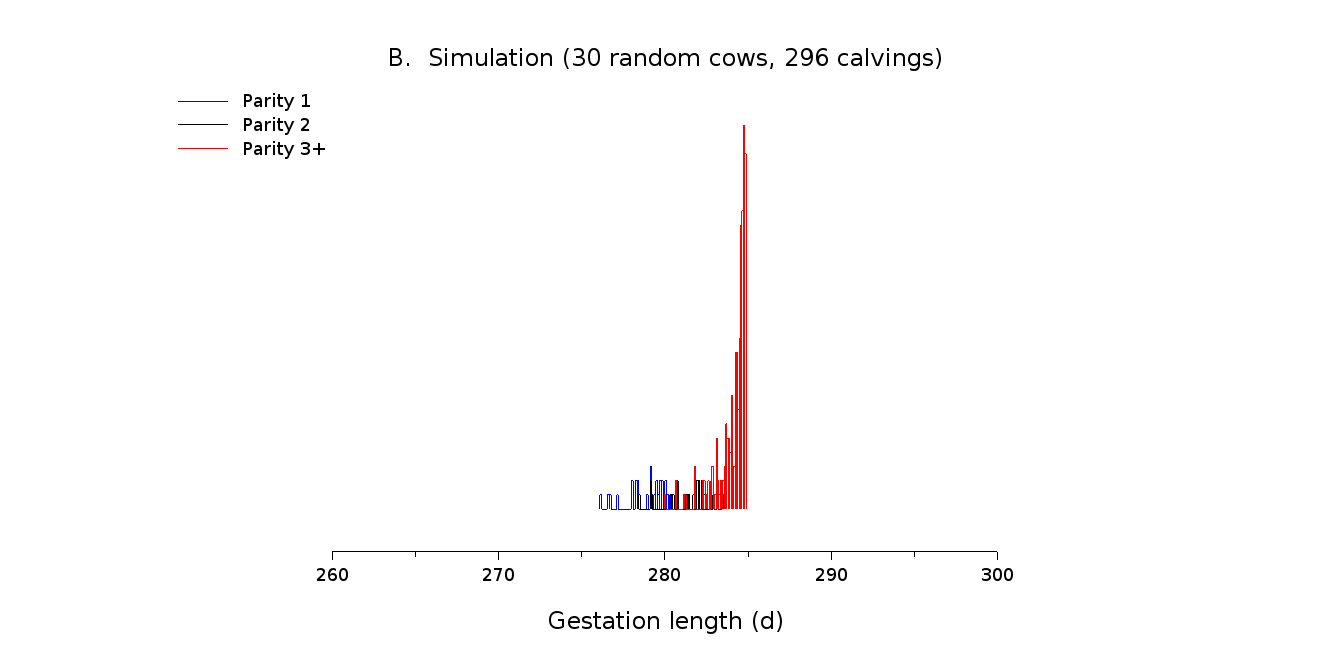
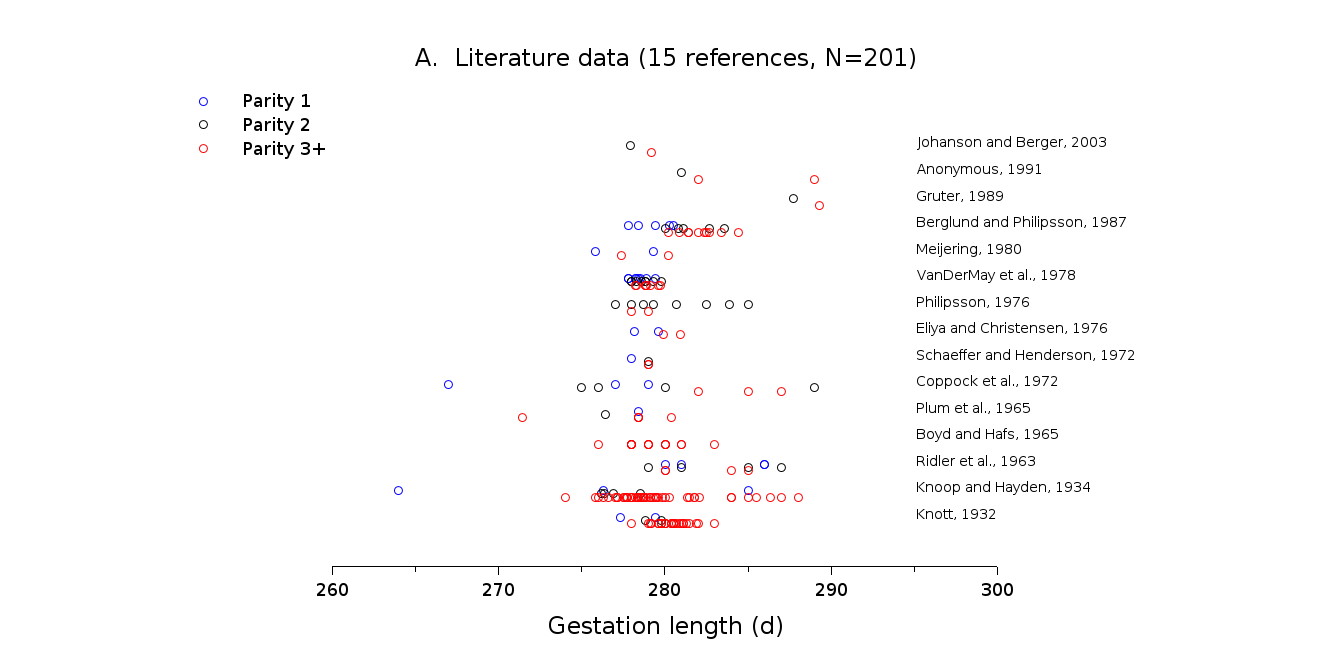
****

Figure S16 Gestation Length (d) according to parity. A: literature data in dairy cattle (15 references[[9]](#footnote-9)). B: Distribution of model simulation for 30 random individual cows performing 296 calvings over 5000d-lifetime.

Comment on Figure S16. Model simulations exhibit a lower gestation length in multiparous cows, which is a trend often observable within reference in literature data. (Gestation lengths are limited to a theoretical value of 285 days in the model)

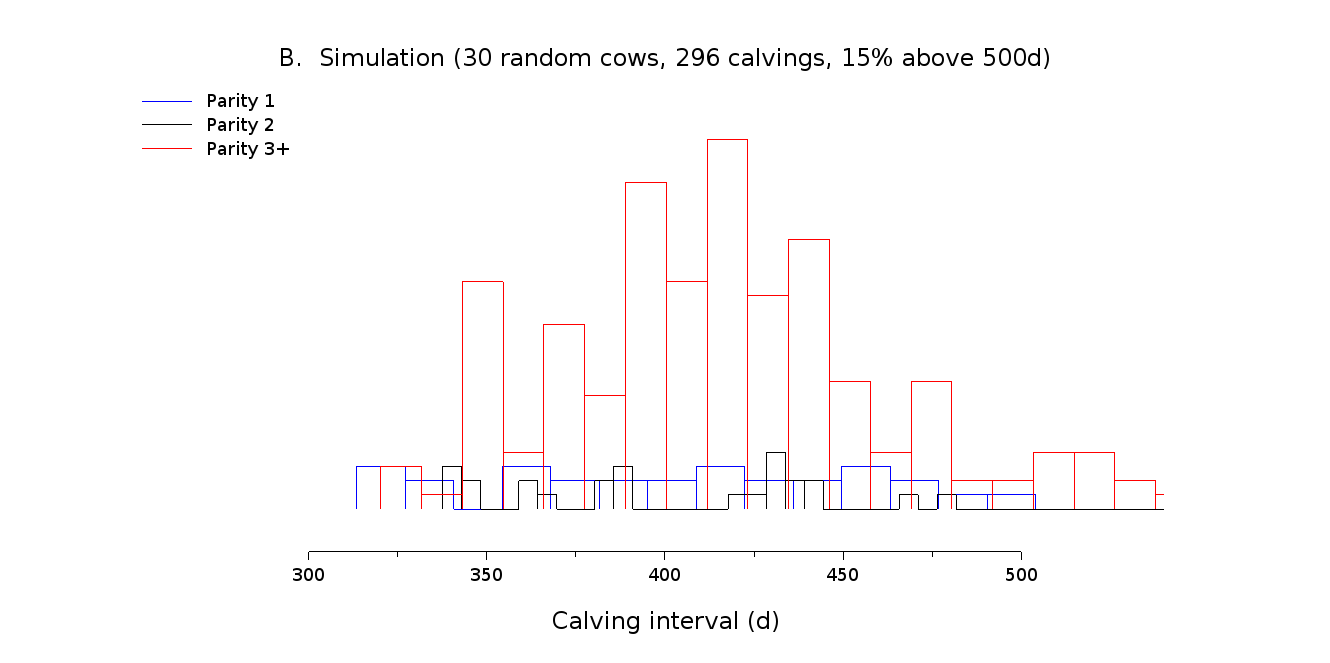
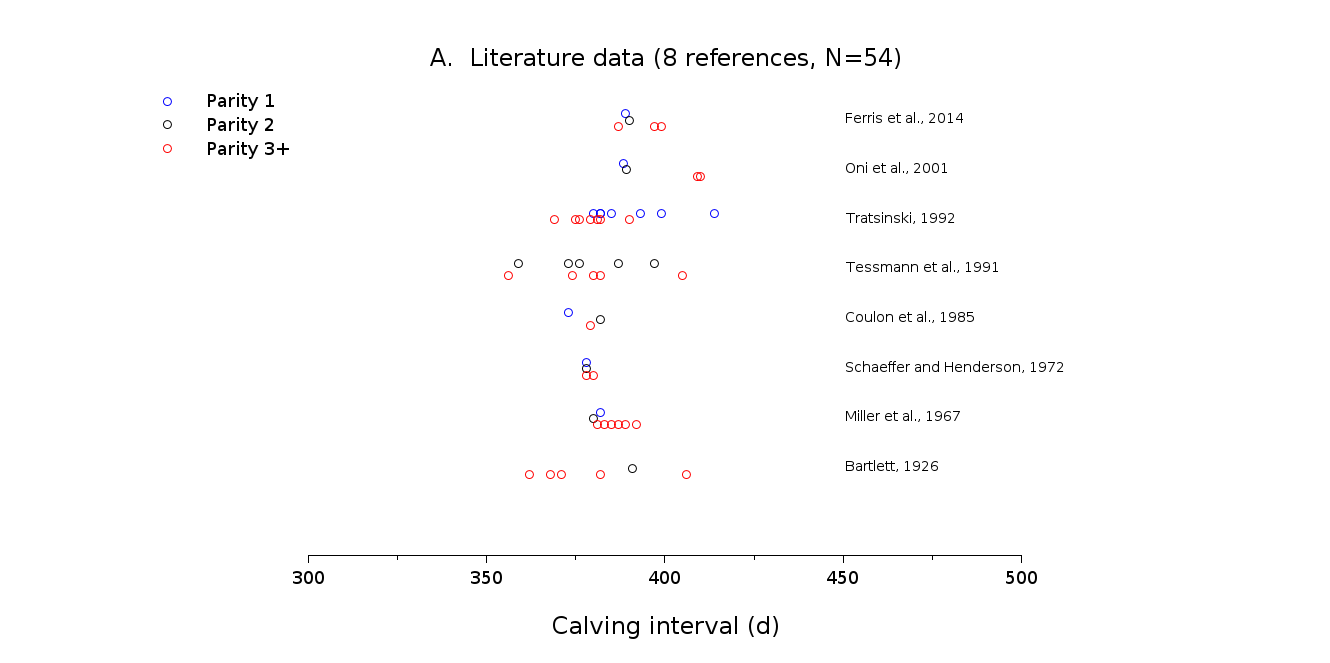
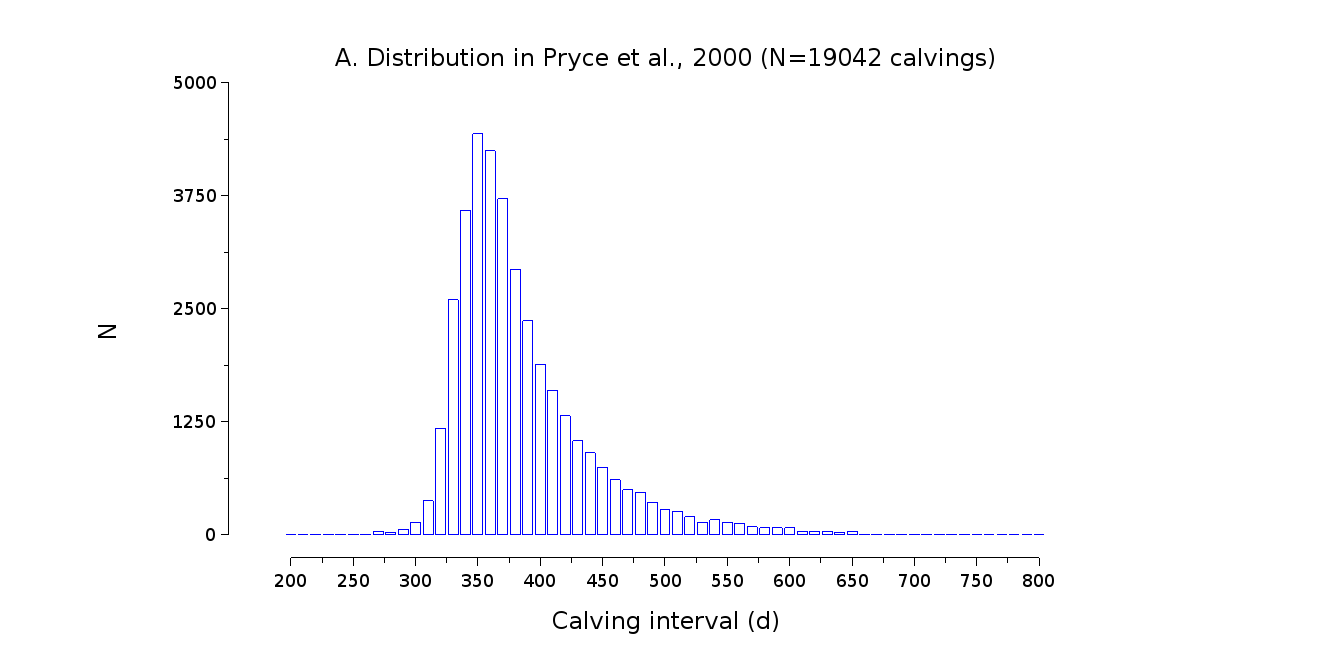
****

Figure S17 Calving interval (d) according to parity. A: literature data in dairy cattle (8 references[[10]](#footnote-10)). B: Distribution of model simulation for 30 random individual cows performing 296 calvings over 5000d-lifetime.

Comment on Figure S17. Model simulations exhibit longer calving interval as compare to literature data. Model simulations exhibit shorter intervals for primiparous cows than for multiparous cows, which is not clearly observable in literature data, but which is globally consistent with the tendency of alteration of fertility with age.

****

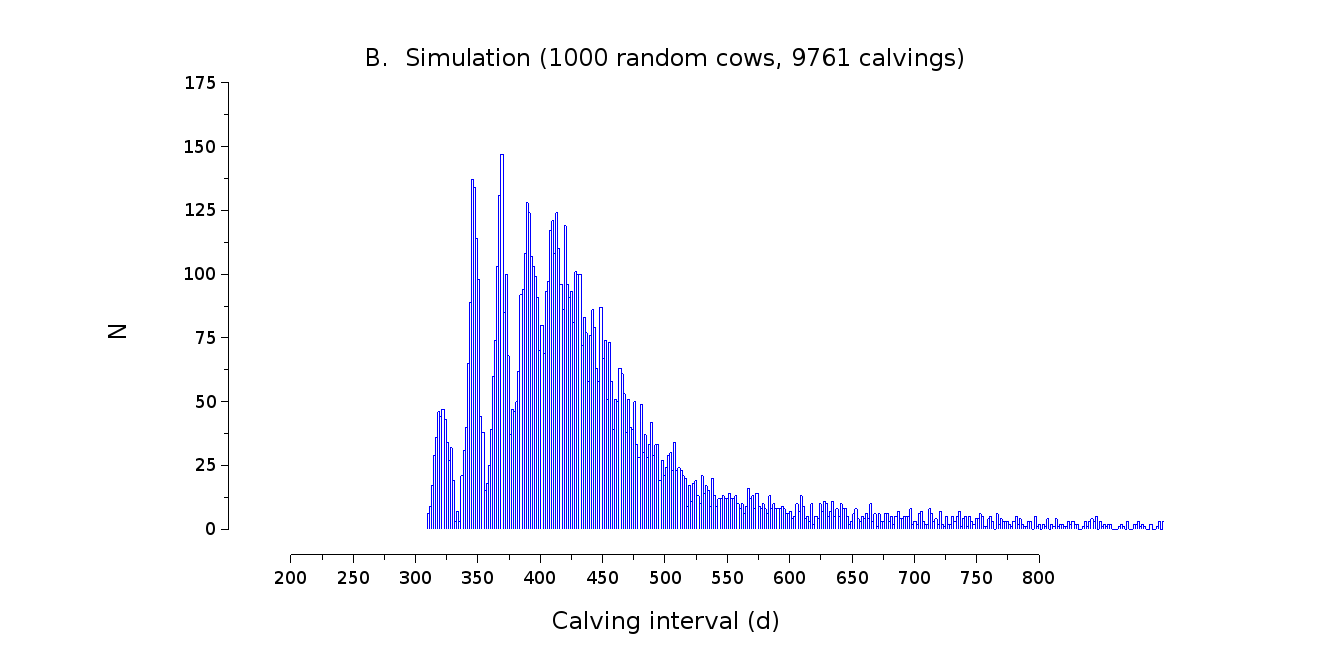
****

Figure S18 Distribution of calving interval (d). A: data in Pryce et al., 2000 (N = 19042 calvings). B: Distribution of model simulation for 1000 random individual cows performing 9761 calvings over 5000d-lifetime.

Comment on Figure S18. Model simulations exhibit a globally consistent distribution but longer calving interval as compare to this dataset. Model simulations exhibit a pattern with a series of approximatively 21d-spaced peaks. This emergent result is consistent with the cyclic nature of the model. This pattern is the trace the number of estrous cycles before cows get pregnant. The model also exhibit an extended occurrence of rare events of very long calving intervals more pronounced than in the dataset.

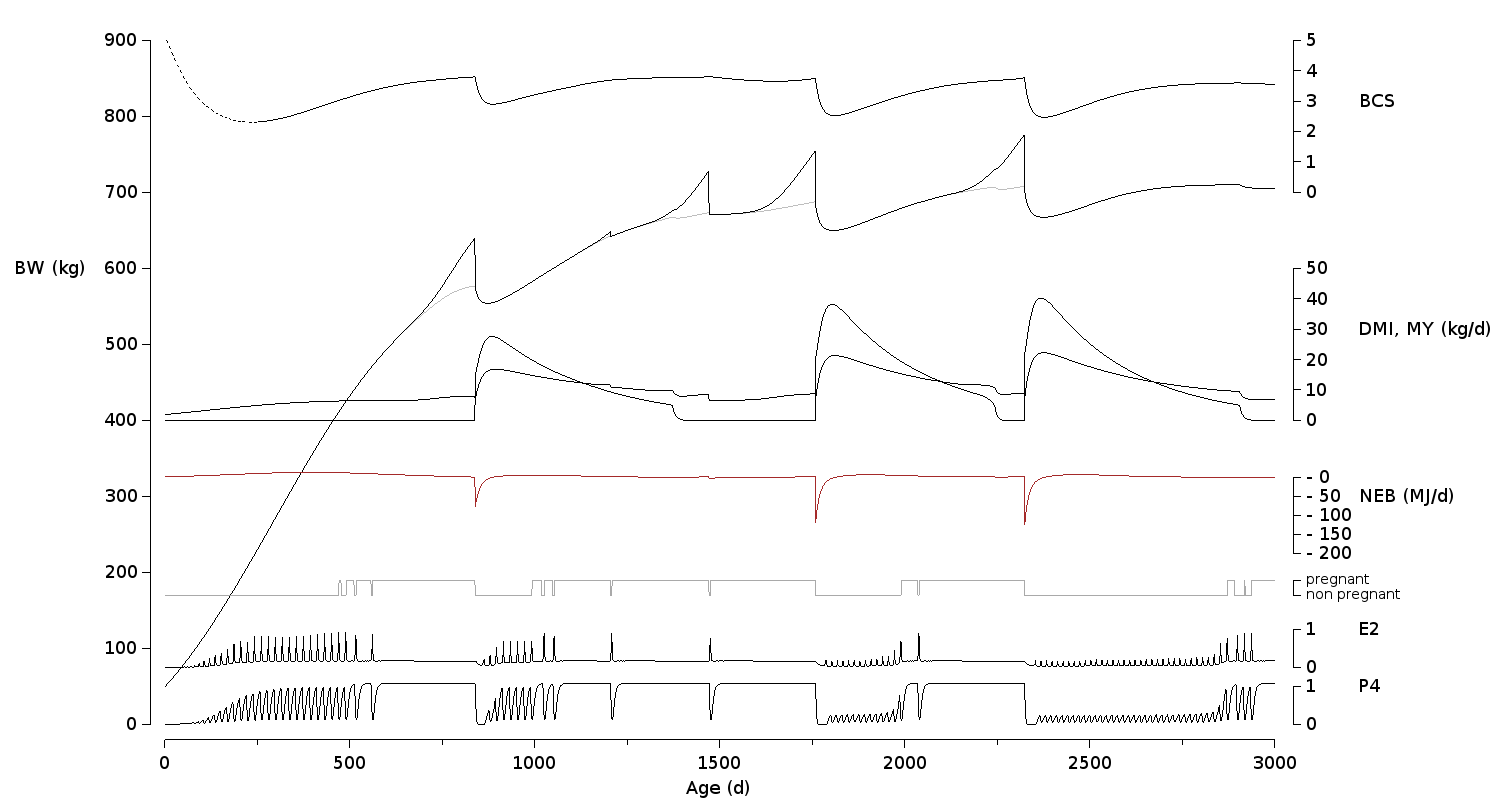
****

Figure S19 Model simulation (BW, BCS: Body Condition Score, DMI: Dry matter intake, MY: Milk Yield, NEB: Net Energy Balance, E2: Estradiol, P4: Progesterone) over 3000d lifetime for the individual cow with highest calving interval (mean calving interval of 795±199 days; 3 calvings).

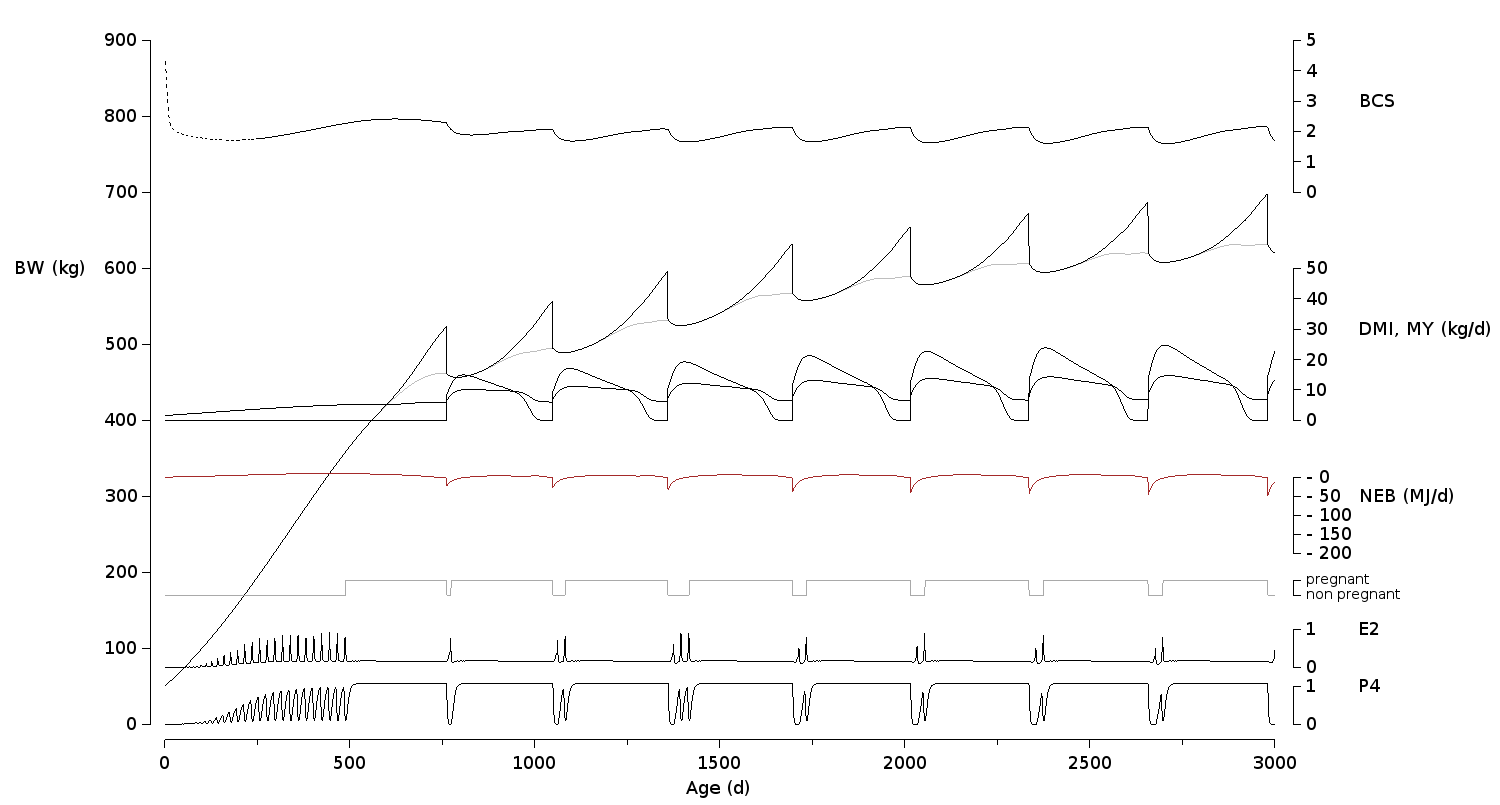


Figure S20 Model simulation (BW, BCS: Body Condition Score, DMI: Dry matter intake, MY: Milk Yield, NEB: Net Energy Balance, E2: Estradiol, P4: Progesterone) over 3000d lifetime for the individual cow with lowest calving interval (mean calving interval of 318±14 days ; 8 calvings).

Material S1 Farm management

# Introduction

As described in the paper, the simulation model simulates multiple individual cows to create a herd. To be able to regulate the herd dynamically through time, it is necessary to define a set of herd management rules (what is the voluntary waiting period, what method of estrous detection is used, etc.). Since these rules are likely to differ between farms, a specific language was written to be able to model farmers’ decisions. The language is based on TCA: a formalism that defines links between Triggers, Conditions and Actions. In this formalism, a set of conditions is checked when something happens (*i.e.*, a trigger occurs). If all conditions are true, specific actions are performed. As TCA may model any decision making process, a language specific to farm management was defined to model the farmers’ decisions and actions.

A configuration file is used to describe the different pieces of code that can be adjusted to simulate a specific farm.

# Farm System Model (FSM)

## Initialization

The init block (Textbox 1) defines the parameters of the simulators. Begin\_date and end\_date define the range of the simulation. Dates must be written as year-month-day hours:minutes:seconds. Note that the time system is monotonous, and never uses daylight saving time.

init{

name = simulation\_test #usefull for tracking only (can be omitted)

output\_db = out/test.sqlite3 #path to the output database

begin\_date = 2015-01-01 00:00:00 #yyyy-mm-dd hh:mm:ss

end\_date = 2020-01-01 00:00:00 #yyyy-mm-dd hh:mm:ss

}

Textbox 1 Example of init{ } code block for initialization.

## States

Cows can be assigned to user defined states (*i.e.*, groups of cows) with the state block (Textbox 2). By default, the program defines the states herd, heifers and not\_heifers. Individuals are automatically added/removed from these states at the appropriate time. Herd contains all cows, heifers contains all cows that have never had a parturition, and not\_heifers all the cows that already had at least one calving.

A cow can be moved from a state xxx to an other state yyy, with the action move xxx yyy. If the cow is not originally in xxx, the action move is not performed. A cow can be added to a state xxx with the action state\_add xxx, and removed from a state xxx with the action state\_delete xxx.

When a cow is added to a state xxx where she doesn’t belong, enter xxx is triggered. When a cow is removed from a state she’s in, the action quit xxx is triggered.

Whether a cow is currently in state xxx is checked with the condition is\_in xxx.

state{

state = a\_group\_name

state = an\_other\_name

}

Textbox 2 Example of state{ } code block to define groups of cows.

## Insemination breed

Breeds of semen used for insemination must be declared in a breed block (Textbox 3). Such breeds are used later to define insemination methods and to check the condition is\_breed. A breed block can contain any number of breeds.

breed{

breed = pure

breed = crossed

}

Textbox 3 Example of breed{ } code block to define breed of semen.

## Insemination method

Different insemination methods (*e.g.*, bull, artificial insemination with regular semen, artificial insemination with sexed semen) influence the chance of an insemination being successful through differences in sperm quality. Therefore, insemination methods including sperm quality and ratio of female spermatozoa needs to be defined (Textbox 4).

insemination\_method{

name =my\_insemination

breed=xx # optional, default = "unknown"

sperm\_quality = 0.9 # default = 1

female\_ratio = 0.5 # 0.5 for regular, 0.9 for sexed semen

}

Textbox 4 Example of insemination\_method{ } code block.

The sperm quality is multiplied with the probability of insemination success as computed by the reproduction model to decide whether an insemination is successful. Therefore, a sperm quality of 0 will never be successful, and a quality of 1 means successful only if the other variables in reproduction are favorable.

Insemination methods can be mixed within the herd (*e.g.*, sexed semen in 10% of the cows, and regular semen in the other 90%). Proportions can be defined with the insemination\_proportions block code (Textbox 5).

insemination\_proportions{

name =my\_insemination

#AInumber method proportion

proportion = 1 aaa 0.9

proportion = 1 xxx 0.1

proportion = 2 yyy 1.0

}

Textbox 5 Example of insemination\_proportions{ } code block.

The insemination\_proportion table is used in the same way insemination\_method is, by referencing its name. The number in the proportion line defines the AI number (1 for first AI, this number is reset at parturition). Method is the name of the previously defined insemination method, and proportion defines how often this method is used for this AI number.

Note that when the AI number is higher than the maximum number defined in this table, we use the maximum number defined, for example, AI number 3 will automatically be inseminated with yyy.

*Feeding method*

Feeding methods are defined by setting an energy density (input parameter eD in MJ/kg DM). Any number of feeding\_method can be defined by duplicating the example block (Textbox 6). Feeding methods are used with the action change\_food xxx, where xxx is a feeding method name.

feeding\_method{

name = standard\_diet

eD = 12.3 # default energy density in MJ/kg DM

}

Textbox 6 Example of feeding\_method{ } code block.

# Estrous Behavior Model (EBM)

The Estrous Behavior Model generates and provides observed\_estrous events to the Farm System Model (FSM). True observed\_estrous events are generated from the estradiol (E2) curve provided by the Reproductive Function Model (RFM). False observed\_estrous events are generated randomly. From the point of view of FSM, true and false observed\_estrous cannot be distinguished. The estrous detection methods are configured in an estrous\_detection\_method block (Textbox 7).

estrous\_detection\_method{

name=watch\_cow

#estradiol is transformed to an expression using a sigmoid function

expression\_threshold=0.75; #default 0.75

expression\_stiffness=7; #default 7

#When do we observe oestruses

#Expression outside a time slice is considered as null

time\_slice = 08:00:00 09:00:00 #observation times : from 08am to 09 am

time\_slice = 16:00:00 17:30:00 #observation times : from 04pm to 05:30pm

#When we decide that expression is strong enough

detection\_threshold=0.104 #1.0\*(2.5/24), as we observe 2.5 hours.

#then, the estrus is truly detected with a chance of

sensitivity = 0.95;

#Independently, an average of wrong\_estrus\_per\_day are generated

wrong\_estrus\_per\_day = 0.002;

}

Textbox 7 Example of estrous\_detection\_method{ } code block.

*Generating true observed\_estrous*

From E2 to estrous\_expression. EBM receives an E2 value from RFM every 15 minutes. This value is converted to an estrous expression by applying a sigmoid function to it (Figure S21). From a biological point of view this can be seen as a smooth threshold function: low E2 values leads to no expression, while high E2 values leads to strong expression.

The sigmoid curve can be parametrized by changing the expression\_threshold and expression\_stiffness parameters of the estrous\_detection\_method.

*From estrous\_expression to observed\_expression.* Some estrous detection methods like accelerometers work all day long, some others, like visual detection, work only during predefined periods. To define when expression is actually observed, we define observation time slices. The observed expression is equal to estrous\_expression when in a time slice, and to 0 outside the slice.

Time slices can be configured by writing time\_slice=hh:mm:ss hh:mm:ss lines in the estrous\_detection\_method block.

*From observed\_expression to potential\_observed\_estrous*. The farmer concludes that there is an estrous if he observes many weak expression signs in a small time period, or a single strong sign. This is modeled by storing the history of observed\_expressions, and multiplying the observed\_expression by a time dependent function called the memory\_function (Figure S22 ). The older the observed\_expression is, the lower the memory\_function is. The memory function is forced to 0 for observed\_expression older than 48 hours, linearly increases between 48 hours to 24 hours, and is equal to 1 for observed\_expression no older than 24 hours.

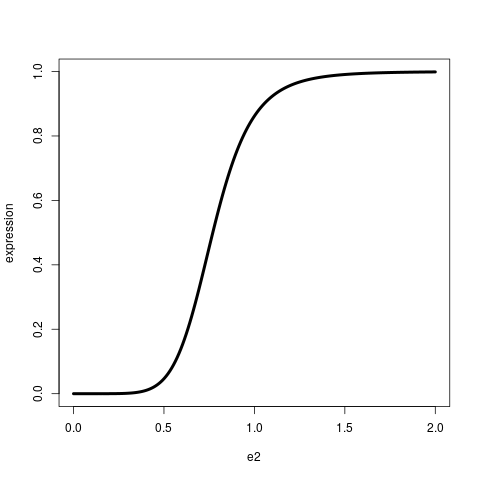
Then observed\_expression\*memory\_function is integrated through time from 48 hours ago to current time. The result of this integral describes how strongly the decision maker (farmer, accelerometer algorithms, …) believes that there is an estrous. When this value is above the detection\_threshold, there is a potential\_observed\_estrous. As this value may stay high for a while, the estrous detection model will not generate any new potential\_observed\_estrous during 10 days. Note that the detection\_threshold has to be adjusted according to time\_slices.

*From potential\_observed\_estrous to observed\_estrous.* A potential estrous has a probability of sensitivity of being detected. When detected, the observed\_estrous event is triggered by the model. When not detected, a missed\_estrous event is triggered. This last event is never seen by the farmer, and is useful only for logging and diagnosis.

*Generating false observed\_estrous*

An independent model randomly generates false observed\_estrous events with an average of wrong\_oestrus\_per\_day. Note that this model is totally independent of the true observed\_estrous models, and will therefore ignore time\_slices.

When no estrous detection method is used, no false observed\_estrous is generated.



**Figure S21** Dairy cow Estrous Behavior Model (EBM): estrous expression function.

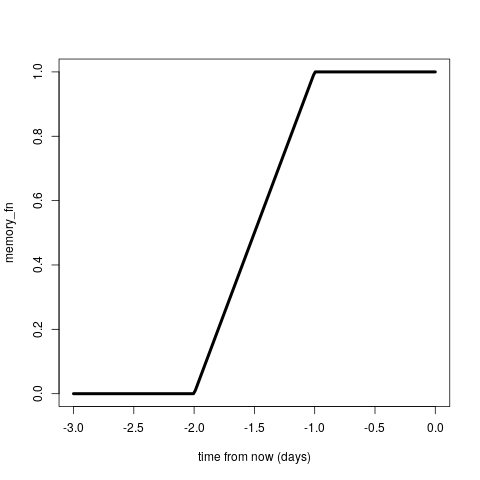


Figure S22 Dairy cow Estrous Behavior Model (EBM): memory function.

# Triggers, conditions and actions

## Triggers

### Predefined triggers are already defined for the model, and the model triggers them at the appropriate timing for each cow (Table S6 ).

*Custom delay triggers.* Delays are generated some days after the after\_trigger trigger (Textbox 8). They simply pass the original message, to the right destination, but at a later moment in time. They can therefore be mixed with the same kind of actions and conditions as the ones compatible with the after\_trigger trigger.

trigger{

type = delay

name = 12h\_later

after\_trigger = an\_other\_trigger

duration = 0.5 #0.5days

}

Textbox 8 Example of trigger{ } code block with custom delay.

*Custom chron triggers.* Chron triggers are broadcasted to all cows in a state according to a time scheme. A time scheme is a date, in format yyyy-mm-dd hh:mm:mm, where some digits can be replaced by \* to indicate ‘every’. For example, every 3rd of the month at 8h00 is \*-\*-03 08:00:00.

trigger{

type = chron

name = every\_day

state = xxx #broadcast this trigger to all cow in this state

scheme = \*-\*-\* 08:00:00 #every day at 08h00

}

Textbox 9 Example trigger{ } code block with custom time scheme.

## Conditions

### Conditions are used to test something, for instance the age of a cow, the sex of a newborn calf or the size of the herd. For each defined condition xxx, not xxx, defines the opposite condition. Threshold conditions allow to compare a variable of a cow (i.e., type = one cow) to a threshold. These conditions are expressed as: a\_variable op value, where a\_variable is the variable to check, op an operator (>, <, >=, <= , ==) and value any number. Missing values (i.e., NaN : Not a Number) always return false for all conditions they are used for.

Triggers, conditions and actions are associated by writing links (Textbox 10). When any trigger occurs, all conditions are checked. If all of them are true, all actions are performed.

#Example : remove non pregnant heifers older than 600 days

link{

trigger = every\_day  
 condition = is\_in heifers  
 condition = age >= 600  
 condition = not\_pregnant

action = delete\_cow

}

Textbox 10 Example of link{ } code block.

### Predefined conditions are already defined in the program (Table S**7** ). Like all conditions, they are tested when the associated trigger occurs. Note that the type of the trigger has to be compatible with the type of the condition. The main variables that can be used in threshold conditions are given in Table S**8** .

*Actions*

The list of predefined actions performed by the model is given in **Table S9**.

## Mix compatible triggers, conditions and actions

### When a trigger occurs, it generates a message that is passed to the conditions and the actions. In order to write links that make sense, compatible messages must be used. For example the triggers of type one cow will generate a message that includes a cow\_id. This cow\_id is required by the conditions that check something on the cow and by the actions that perform something on this cow.

### Some conditions and actions noted by a type doesn't read any message, and can therefore be linked to any trigger. Nevertheless, even if the code should work they probably make sense only in a particular context. This is the case, for example, for the actions buy\_cow and buy\_calf that should be associated to the trigger init, but that can be written anywhere.

**Table S6** *Farm System Model (FSM): Predefined triggers*

|  |  |  |
| --- | --- | --- |
| Trigger | Type | Definition |
| Initialization |  |  |
| Init | Init | Triggered at start of simulation |
| Reproduction |  |  |
| Conception | one cow | Triggered when an insemination is successful |
| Parturition | one cow | Triggered when a viable calf is born |
| Abortion | one cow | Triggered when an embryo or fetus is lost |
| Mature | one cow | Triggered when the cow is sexually mature and starts cycling |
| Insemination | one cow | Triggered when the cow is inseminated |
| Estrous | one cow | Triggered when an estrous is observed. This event is triggered only if the estrous is strong enough to be inseminated |
| Milk production |  |  |
| start\_milking | one cow | Triggered when milking starts |
| stop\_milking | one cow | Triggered when milking stops |
| States |  |  |
| enter xxx | one cow | Triggered when a cow is added to the state xxx, if the cow is not already in the state xxx |
| quit xxx | one cow | Triggered when a cow is removed from the state xxx, if the cow is already in the state xxx |
| Miscellaneous |  |  |
| Death | one cow | Triggered when the cow dies |
| Calving | newborn calf | Triggered when a viable calf is born |

**Table S7** *Farm System Model (FSM): Predefined conditions*

|  |  |  |
| --- | --- | --- |
| Condition | Type | Help |
| States |  |  |
| is\_in xxx | one cow | True if the cow is in state xxx, false otherwise |
| state\_size xxx >= 45 | any | Compare the number of animals in state xxx to a number. Valid comparaison operators are <, >, <=, >=. Note that they must be separated from text with spaces |
| Cow status |  |  |
| is\_pregnant | one cow | True if the cow is pregnant. Pregnancy starts at conception, and finishes at abortion or parturition |
| is\_mature | one cow | True if the cow is sexually mature (and is therefore cycling) |
| is\_milking | one cow | True if the cow is milked (*i.e.*, tracks start\_milking and stop\_milking) |
| a\_variable >= 45 | one cow | Compare to threshold |
| Calf status |  |  |
| calf\_breed xxx yyy | newborn calf | True if the semen used to produce this calf was of breed xxx, or yyy |
| calf\_sex xxx | newborn calf | True if the calf has the required sex (xxx is male or female). This condition makes sense only with the calving trigger. Note that males are never added to the herd, they disappear just after calving |

**Table S8** *Farm System Model (FSM): Variables*

|  |  |
| --- | --- |
| Variable | Help |
| num\_cycle | Cycle number. This number is reset at parturition |
| parity | Heifers have parity = 0. Primiparous have parity = 1, etc.  Parity increases by one at parturition |
| num\_insemination | Insemination number. This number is set to 0 at parturition |
| milk\_yield | Milk yield in kg/day. As low milk yields may happen before and after the peak, this condition is combined with a condition on the day from calving to detect the end of lactation |
| body\_weight | Body weight in kg |
| body\_condition\_score  (or bcs) | 0 is the lowest score, 5 the highest one. Values out of the 0-5 range mean that the energy density of the ration is too far from a realistic cow ration |
| days\_after\_calving  (or dim) | This value is NaN for heifers. Starts at calving, set to 0 at parturition. Abortions are not considered as calving, and therefore do not change this value |
| days\_in\_pregnancy  (or dip) | This value is NaN when not pregnant. Start at conception, set to NaN at parturition |
| days\_after conception | This value is NaN before the first conception. Starts at conception, set to 0 at conception |
| age | Age is in days after birth |

**Table S9** *Farm System Model (FSM): Predefined actions*

|  |  |  |  |
| --- | --- | --- | --- |
| Action | Argument | Type | Help |
| Estrous detection |  |  |  |
| estrous\_start | xxx | one cow | Start detecting oestrous using the xxx method (see estrous\_detection\_method) |
| estrous\_stop | - | one cow | Stop detecting oestrous |
| Reproduction |  |  |  |
| inseminate | xxx | one cow | Inseminate the cow with an insemination method named xxx (see insemination\_method) or according to insemination proportions (see insemination\_proportions) |
| force\_conception | breed\_name  female\_ratio | one cow | Generate a successful conception, as if the cow was inseminated with breed\_xxx (see breed) with a female ratio of female\_ratio (*i.e.*, a number between 0 for all males, and 1 for all females) |
| Milking |  |  |  |
| start\_milking | - | one cow | Start milking |
| stop\_milking | - | one cow | Stop milking (with condition = is\_milking) |
| Feeding |  |  |  |
| change\_food | xxx | one cow | Change the current food to xxx (see feeding\_method) |
| Population management |  |  |  |
| buy\_cow | calf\_breed  female\_ratio  cow\_age dfc cow\_days\_in\_pregnancy  num\_cows | any | Buy cows  - calf\_breed is the breed of the semen used to inseminate this cow (see breed)  - female\_ratio is the sex ratio of the semen used to inseminate this cow  - cow\_age is the age of this cow in days from birth  - dfc is the number of days from conception of this cow, if the cow is not pregnant, write no\_conception instead  - cow\_days\_in\_pregnancy is the number of days in pregnancy of this cow  - num\_cow is the number of cow to buy |
| buy\_calf | calf\_breed  number | any, init | Buy number of female calves of breed calf\_breed (see breed ). |
| delete\_cow | info | one cow | Delete this cow, info can be any message that has to be logged |
| delete\_calf | info | newborn calf | Delete this calf, info can be any message that has to be logged. This action only makes sense with the calving trigger |
| Log |  |  |  |
| log | info | one cow | Log info to the default logger (here standard output) |
| log\_cout | info | one cow | Log info to the standard output |
| log\_db | info | one cow | Log info to the database |

1. Eckles, 1920; McCandlish, 1922; Bartlett, 1926a; Bartlett, 1926b; Espe et al., 1932; Ragsdale, 1934; Hilder and Fohrman, 1949; Ellenberger et al., 1950; Reid et al., 1951; Campbell an Flux, 1952; Matthews and Fohrman, 1954; Davis and Hathaway, 1956; Morrison, 1956; Burt, 1957; Davis, 1957; Crichton et al., 1959; Crichton et al., 1960; Swanson, 1960; Martin et al., 1962; Wickersham and Schultz, 1963; Swanson and Hinton, 1964; Bath et al., 1965; McDaniel and Legates, 1965; Miller et al., 1967; Swanson, 1967; Hollon et al., 1972; Rakes and Davenport, 1972; Lamb and Barker, 1975; Grieve et al., 1976; Berglund et al., 1980; Herland and Wiktorsson, 1982; Lee et al., 1982; Fisher et al., 1983; Lebengarts et al, 1984; Butler-Hogg et al., 1985; Lin et al., 1985; Reddy and Basu, 1986; Ribas and Ponce de Leon, 1986; Heinrichs and Hargrove, 1987; Johnson et al., 1987; Pikina, 1987; Polyakov et al., 1987; Singh and Bath, 1987; Hocking et al., 1988; Moore et al., 1990; Akbulut et al., 1993; Berg and Ekern, 1993; Grabowski et al., 1993; Peri et al., 1993; Andrew et al., 1994; Dhour et al., 1995; Groen and Vos, 1995; Hoffman et al., 1996; Koenen and Groen, 1996; Kunzi et al., 1996; Colburn et al., 1997; Hoffman, 1997; Kertz et al., 1998; Vacek et al., 1999; Freetly et al., 2000 [↑](#footnote-ref-1)
2. Waltner et al., 1993; Hoffman, 1997; Kertz et al., 1997; Van Amburgh et al., 1998; Drame et al., 1999; Abeni et al., 2000; Koenen et al., 2001; Mao et al., 2004; Shamay et al., 2005; Berry et al., 2006. [↑](#footnote-ref-2)
3. Broster et al., 1969; Broster et al., 1975; Cowan, 1970; Decaen, 1970; DePeters, 1985; DePeters, 1989; Everson et al., 1976; Garnsworthy and Topps, 1982; Holter et al., 1982; Holter et al., 1984; Holter et al., 1992; Holter et al., 1993; Johnson, 1977; Johnson, 1979; Johnson, 1983; Kertz et al., 1991; Kronfeld et al., 1980; Krohn et al., 1983; Llahr et al.,1983; Lodge et al., 1975; Mohrenweiser and Donker, 1967; Ostersen et al., 1997; Pinchasov et al., 1982; Rook and Campling, 1965; Soder and Holden, 1999; Staples et al., 1990; Swanson, 1967; Taylor and Leaver, 1984a; 1984b; Tolkamp et al., 1998; Vérité and Journet, 1977; Wallace, 1959; Wiktorsson, 1971; Wiktorsson, 1973; Wohlt and Clark, 1978; Wohlt et al., 1991. [↑](#footnote-ref-3)
4. Broster et al., 1969; Broster et al., 1975; Cowan, 1970; Decaen, 1970; DePeters, 1985; DePeters, 1989; Everson et al., 1976; Garnsworthy and Topps, 1982; Holter et al., 1982; Holter et al., 1984; Holter et al., 1992; Holter et al., 1993; Johnson, 1977; Johnson, 1979; Johnson, 1983; Kertz et al., 1991; Kronfeld et al., 1980; Krohn et al., 1983; Llahr et al.,1983; Lodge et al., 1975; Mohrenweiser and Donker, 1967; Ostersen et al., 1997; Pinchasov et al., 1982; Rook and Campling, 1965; Soder and Holden, 1999; Staples et al., 1990; Swanson, 1967; Taylor and Leaver, 1984a; 1984b; Tolkamp et al., 1998; Vérité and Journet, 1977; Wallace, 1959; Wiktorsson, 1971; Wiktorsson, 1973; Wohlt and Clark, 1978; Wohlt et al., 1991. [↑](#footnote-ref-4)
5. Broster et al., 1969; Broster et al., 1975; Cowan, 1970; Decaen, 1970; DePeters, 1985; DePeters, 1989; Everson et al., 1976; Garnsworthy and Topps, 1982; Holter et al., 1982; Holter et al., 1984; Holter et al., 1992; Holter et al., 1993; Johnson, 1977; Johnson, 1979; Johnson, 1983; Kertz et al., 1991; Kronfeld et al., 1980; Krohn et al., 1983; Llahr et al.,1983; Lodge et al., 1975; Mohrenweiser and Donker, 1967; Ostersen et al., 1997; Pinchasov et al., 1982; Rook and Campling, 1965; Soder and Holden, 1999; Staples et al., 1990; Swanson, 1967; Taylor and Leaver, 1984a; 1984b; Tolkamp et al., 1998; Vérité and Journet, 1977; Wallace, 1959; Wiktorsson, 1971; Wiktorsson, 1973; Wohlt and Clark, 1978; Wohlt et al., 1991. [↑](#footnote-ref-5)
6. Buchem, 1909; Bergmann, 1921; Hammond, 1927; Esskuchen, 1931; Swett et al., 1937; Hatch et al., 1941; Winters et al., 1942; Nichols, 1944; Swett et al., 1948; Ellenberger et al., 1950; Becker et al., 1951; Melton et al., 1951; Mäkelä, 1956; Joubert et Van Marle, 1959; Lyne, 1960; Hubbert et al., 1972; Ferrell et al., 1976; Eley et al., 1977; Chew et al., 1979; Anthony et al., 1986; Sultan et al., 1987; Bellows et al., 1990; Reynolds et al., 1990; Ferrell, 1991; House and Bell, 1993; Okano, 1994; Zhang et al., 1999. [↑](#footnote-ref-6)
7. .Eckles, 1916; Henry and Morrison, 1917; Eckles, 1919; Fitch et al., 1924; Joubert and Van Marle, 1959; Ridler et al., 1963; Wickersham and Schultz, 1963; Swanson and Hinton, 1964; Broster and Tuck, 1967; Gleeson, 1973; Lodge et al., 1975; Yadava et al., 1976; Gardner et al., 1977; Heitzman et al., 1979; Huth and Schmidt, 1979; Østergaard, 1979; Erb et al., 1981; Laird et al., 1981; Collier et al., 1982; Holter et al., 1986; Berglund and Philipsson, 1987; Stelwagen and Grieve, 1992; Kume and Bicoku, 1993; Lacasse et al., 1993; Troccon, 1993; Moore, 1994; Troccon et al., 1994; Kertz et al., 1997; Hansen et al., 1999; Negash, 1999; Keady et al., 2001; Johanson and Berger, 2003. [↑](#footnote-ref-7)
8. .Eckles, 1919; Fitch et al., 1924; Dinkhauser et al., 1944; Ellenberger et al., 1950; Brakel et al., 1952; Davis et al., 1954; Foote et al., 1959; Huth, 1962; Ridler et al., 1963; Andersen et al., 1965; Boyd and Hafs, 1965; Everett and Magee, 1965; Touchberry and Bereskin, 1966; DeTena Andreu, 1973; Romita, 1973; Beardsley et al., 1974; Gianola and Tyler, 1974; Hocking, 1974; Koubek, 1974; Muller and Owens, 1974; Oldenbroek, 1974; Anonymous, 1975; Dijkstra et al., 1975; Beardsley et al., 1976; Eliya and Christensen, 1976; Guaragna et al., 1976; Manrique et al., 1976; Osinga and Ogink, 1976; Philipsson, 1976; Serrano et al., 1976; Laurijsen and Oldenbroek, 1977; Morgan, 1977; Everitt et al., 1978; Fisher and Williams, 1978; Gaillard, 1978; Martinez et al., 1978; Veris, 1978; Arbaban-Ghafouri, 1980; Egbunike and Togun, 1980; Gaillard, 1980; Lazarevic and Novakovic, 1980; Meijering, 1980; Chew et al., 1981; Erb et al., 1981; Gaillard, 1981; Leeuwen and Ziljstra, 1981; Little and Harrison, 1981b; Gaillard, 1982; Das et al., 1984; Oldenbroek, 1984; Bhuyan and Mishra, 1985; Oferrall et al., 1985; VonKorn and Langholz, 1985; Holter et al., 1986; Sang et al., 1986; Shin et al., 1986; Berglund and Philipsson, 1987; Eppard et al., 1987; Trilk et al., 1988; Gravert et al., 1990; Guilbault et al., 1990; Hagger and Hofer, 1990; Oferrall and Ryan, 1990; Rooy et al., 1990a; Rooy et al., 1990b; Anonymous, 1991; Rémond et al., 1991; KB-Mitteilungen, 1993; Troccon, 1993; Kojima, 1999; Zhang et al., 1999; Jacobsen et al., 2000; Perfield et al., 2002; Johanson and Berger, 2003. [↑](#footnote-ref-8)
9. . Knott, 1932; Knoop and Hayden, 1934; Ridler et al., 1963; Boyd and Hafs, 1965; Plum et al., 1965; Coppock et al., 1972; Schaeffer and Henderson, 1972; Eliya and Christensen, 1976; Philipsson, 1976; VanDerMay et al., 1978; Meijering, 1980; Berglund and Philipsson, 1987; Gruter, 1989; Anonymous, 1991; Johanson and Berger, 2003. [↑](#footnote-ref-9)
10. . Bartlett, 1926; Miller et al., 1967; Schaeffer and Henderson, 1972; Coulon et al., 1985; Tessmann et al., 1991; Tratsinski, 1992; Oni et al., 2001; Ferris et al., 2014. [↑](#footnote-ref-10)