

Supplementary Material

May 2018

LiGAPS-Beef, a mechanistic model to explore potential and feed-limited beef production: 1. Model description and illustration

Supplementary Material belonging to the paper:

LiGAPS-Beef, a mechanistic model to explore potential and feed-limited beef production: 1. Model description and illustration

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# **Preface**

This file with Supplementary Material belongs to the paper ‘LiGAPS-Beef, a mechanistic model to explore potential and feed-limited beef production: 1. Model description and illustration’ (Van der Linden *et al.*, 2018a). The model LiGAPS-Beef is broadly described and illustrated in this paper, and explained in more detail in this supplement. LiGAPS-Beef is a dynamic, deterministic, and mechanistic model that simulates potential and feed-limited beef production for beef production systems across the world. Simulation of potential and feed-limited production allows to assess yield gaps, and identifies the defining and limiting factors underlying the yield gap for cattle. Yield gap analysis is used subsequently to explore options to improve beef production.

The first chapter of the Supplementary Material lists the parameters and input required by LiGAPS-Beef, describes its three sub-models, and explains the upscaling from individual animals to herds in more detail than in the paper. The last part of this chapter describes how LiGAPS-Beef can be operated. The source code of LiGAPS-Beef is freely available (https://doi.org/10.18174/442973), so you are have the opportunity to work with the model yourself. In addition, the source code is freely accessible at the model portal of the Plant Production Systems group of Wageningen University, The Netherlands (http://models.pps.wur.nl/content/ligaps-beef). Updates and model applications will be published on the model portal. The second chapter provides additional information on the model illustration presented in the paper, both at animal and herd level. The development team of LiGAPS-Beef hopes this Supplementary Material will further stimulate the application LiGAPS-Beef and contribute to extension of yield gap analyses in the livestock sciences.

We are extending the model to dairy (LiGAPS-Dairy) and other animal types. New models derived from LiGAPS-Beef will be available on the model portal, when ready. Comments, suggestions, bug reports, and other feedback on LiGAPS-Beef is highly appreciated, and can be sent to the development team by email ([aart.vanderlinden@wur.nl](mailto:aart.vanderlinden@wur.nl)).

Wageningen, March 2018,

LiGAPS-Beef development team

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# 1. Model description

The paper linked to this Supplementary Material describes the model LiGAPS-Beef (Van der Linden *et al.*, 2018a). The aim of this chapter in the Supplementary Material is to describe the model more in more detail. Input parameters for this model are broadly mentioned in the main paper, and are listed individually in section 1.1. LiGAPS-Beef consists of a thermoregulation sub-model, a feed digestion sub-model, and an energy and protein utilisation sub-model (Van der Linden *et al.*, 2018a). Each of these sub-models is described in more detail than in the main paper, and equations are provided in section 1.2-1.4. Equations are sometimes followed by numbers between square brackets. These numbers refer to table numbers (S1-S6) and the parameter numbers within these tables, as given in section 1.1. The model LiGAPS-Beef aims to simulate potential and feed-limited production of complete herds in beef production systems, including reproductive cows. Section 1.5 covers the upscaling from an individual animal to the herd level in more detail than in the main paper. Finally, the information presented in sections 1.1-1.5 is linked to the program code of LiGAPS-Beef in section 1.6.

1.1 Input parameters

This supplement presents six tables with input parameters for LiGAPS-Beef. The weather data required as input by LiGAPS-Beef are daily weather data, because the time step of the model is one day. Daily weather data required are solar radiation, minimum and maximum temperature, vapour pressure, wind speed, and precipitation (Table S1). The conversion from solar radiation on a horizontal surface to coat surface, as well as the cloud cover, can be calculated from the aforementioned climate data. The calculation for the conversion from solar radiation on a horizontal surface to coat surface is given in the Appendix I of this document. Weather data for various countries can be found on the website of the Global Yield Gap Atlas ([www.yieldgap.org](http://www.yieldgap.org)) and the model portal of the Plant Production Systems group of Wageningen University & Research (<http://models.pps.wur.nl/node/1062>).

***Table S1.*** Daily weather data required as input for the thermoregulation sub-model, which simulates heat flows in beef cattle.

|  |  |  |
| --- | --- | --- |
| Weather data | Unit | Name in R-code1 |
| Julian day of the year | - | WEATHER$DOY |
| Solar radiation a | kJ m-2 day-1 | WEATHER$RAD |
| Minimum temperature | °C | WEATHER$MINT |
| Maximum temperature | °C | WEATHER$MAXT |
| Vapour pressure | kPa | WEATHER$VPR |
| Wind speed | ms-1 | WEATHER$WIND |
| Precipitation | mm day-1 | WEATHER$RAIN |
| Conversion radiation to coat b | m2 coat m-2 ground surface | WEATHER$AHA |
| Cloud cover | Ω | WEATHER$OKTA |

1 Weather variables in the R-code are included in the matrix WEATHER. The $ and the consecutive name indicates the column of this matrix.

a Solar radiation on a horizontal surface, also referred to as a ground surface.

b Ratio m2 coat per m-2 horizontal surface

The next tables contain breed and sex-specific parameters (Table S2), feed characteristics (Table S3), heat increment of feeding (Table S4), physical and chemical parameters (Table S5), and lastly the cattle-specific parameters (Table S6).

***Table S2.*** Breed and sex-specific parameters of beef cattle used in the model for the Charolais breed and the ¾ Brahman × ¼ Shorthorn breed (B×S). Eight parameters are used as input for the thermoregulation sub-model, and thirteen for the energy and protein utilisation sub-model. The parameters are found also in section 1.3.1 of the R-code of LiGAPS-Beef.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| # | Parameter | Unit(s)1 | Charolais | | B×S | | Sub-model2 | Name in R-code3 |
|  |  |  | male | female | male | female |  |  |
| 1 | Body area (Body area : weight factor)a |  | 1 | 1 | 1.09 | 1.09 | T | AREAFACTOR |
| 2 | Max. conduction body core – skinb | W m-2 K-1 | 64.1 | 64.1 | 64.1 | 64.1 | T | CBSMAX |
| 3 | Coat lengthc | mm | 12 | 12 | 12 | 12 | T | LC |
| 4 | Min. cond. body core – skind |  | 1 | 1 | 1.225 | 1.225 | T | RBCSf |
| 5 | Reflectance coate |  | 0.6 | 0.6 | 0.56 | 0.56 | T | REFLC |
| 6 | Latent heat release 1f |  | 3.08 | 3.08 | 3.08 | 3.08 | T | LIBRARY[24] |
| 7 | Latent heat release 2f |  | 1.73 | 1.73 | 2.15 | 2.15 | T | LIBRARY[25] |
| 8 | Latent heat release 3f | °C | 35.3 | 35.3 | 35.6 | 35.6 | T | LIBRARY[26] |
| 9 | Birth weightg | kg TBW | 48.1 | 45.9 | 41 | 36.9 | E | BIRTHW |
| 10 | Gompertz constant of integrationh |  | 1.6 | 1.6 | 1.6 | 1.6 | E | CPAR |
| 11 | Gompertz rate constanth |  | 1.1 | 1.1 | 1.5 | 1.5 | E | DPAR |
| 12 | Gompertz reductionh | kg TBW | 316.7 | 228.7 | 187.6 | 144.2 | E | EPAR |
| 13 | Lactation curve 1i |  | - | 8.00 | - | 5.68 | E | MILKPARA |
| 14 | Lactation curve 2i |  | - | 0.068 | - | 0.068 | E | MILKPARB |
| 15 | Lactation curve 3i |  |  | 3.38 × 10-3 |  | 3.38 × 10-3 | E | MILKPARC |
| 16 | Lipid bone parameterj |  | 11.6 | 11.6 | 11.6 | 11.6 | E | LIBRARY[20] |
| 17 | Maintenance correction factork |  | 1 | 1 | 0.93 | 0.93 | E | LIBRARY[18] |
| 18 | Max. carcass fractionl |  | 0.64 | 0.62 | 0.58 | 0.55 | E | LIBRARY[21] |
| 19 | Max. muscle : bone ratiom |  | 4.4 | 4.1 | 4.1 | 3.6 | E | LIBRARY[22] |
| 20 | Maximum adult weightn | kg TBW | 1300 | 950 | 775 | 675 | E | MAXW1 |
| 21 | Min. fraction mature TBW foro gestation |  | - | 0.60 | - | 0.50 | E | LIBRARY[17] |
| 22 | Min. fat tissue in carcass for gestationp | % | - | 32 | - | 20 | E | LIBRARY[19] |

TBW = total body weight.

1 This column is left blanc for dimensionless parameters

2 T = thermoregulation sub-model; E = energy and protein utilisation sub-model.

3 Parameter names in the R-code. Not all parameters from the library have a specific name.

a *B. indicus* cattle have 12% more area (1.12) per unit of body weight than *B. taurus* cattle (1.00) (Johnston *et al.*, 1958). Charolais cattle are *B. taurus* cattle. Since B×S cattle have ¾ *B. indicus* genes and ¼ *B. taurus* genes the increase in area is assumed to be 9% for this breed.

b Maximum conduction between body core and skin (full vasodilatation), calculated from Turnpenny *et al.* (2000b). The parameter is constant with age and is valid for beef cattle. (Turnpenny *et al.*, 2000b)

c Seasonal changes in summer and winter coats are not taken into account. Coat length is adopted from Turnpenny *et al.* (2000b).

d  *B. indicus* cattle are assumed to have a 30% higher conduction between the body core and skin than *B. taurus* cattle. *B. taurus* cattle have the subcutaneous fat tissue distributed over the whole body, which is an insulating layer. The fat tissue of *B. indicus* cattle is more concentrated in the hump.

e Estimated from the coat colour of the breed based on da Silva *et al.* (2003). (Da Silva *et al.*, 2003)

f Maximum latent heat release from the skin (W m-2) = minimum heat release + latent heat release 1 × elatent heat release 2 × (skin temperature – latent heat release 3)) × latent heat of water vapour, based on Gatenby (1986). Skin temperature is is in °C. Parameters are estimated from Schleger and Turner (1964) and Gatenby (1986). *B. taurus* cattle have higher rates of laten heat release than *B. indicus* cattle at high temperatures, but this is reversed at very high temperatures. (Schleger and Turner, 1965, Gatenby, 1986)

g Birth weights of Charolais are from Simčič *et al.* (2006).(Simčič *et al.*, 2006)

h Gompertz curves describing total body weight are written in the form (a + (b – a + e) × e(-c × e(-d × t)) – e. Where a is the birth weight; b is the maximum adult weight; c is the constant of integration; d is the rate constant; t is time in days, and e is a reduction. Parameters c, d, and e are obtained by fitting Gompertz curves.

i The lactation curve is calculated with the formula lactation curve 1 × tlactation curve 2 ×e(-lactation curve 3 × t) (Wood, 1967). Where t is the time in days after parturition.

j Lipid fraction in the bone is calculated as Wb × A × ln(Wb) / 100. Where Wb is the bone weight, and A is the breed specific parameter. This formula is based on data of Field *et al.* (1974). Weight of bones is different between breeds with different mature body weights, there may also be differences in this parameter, but so far no data were available to test this. (Field *et al.*, 1974)

k  *B. indicus* cattle have 9% lower maintenance requirements (0.91) per unit of metabolic body weight than *B. taurus* cattle (1.00), based on Ouellet *et al.* (1998) and NRC (2000). (Ouellet *et al.*, 1998, NRC, 2000)

l Charolais cattle have been bred for beef production, resulting in high carcass percentages. Males are assumed to have larger carcass percentages than females. Maximum carcass percentages of Charolais bulls are estimated from Pfuhl *et al.* (2007) (60.4% at 18 months). Relations between empty body weight and carcass weight are given by Fox *et al.* (1976). (Berg and Butterfield, 1968, Fox *et al.*, 1976, Pfuhl *et al.*, 2007)

m Values are guesstimates. Estimates for muscle:bone ratios were taken from Berg and Butterfield (1968).

n Mature body weights under potential production are hard to estimate. Weights mentioned for Charolaiscattle are higher than the actual slaughter weights mentioned by Reseaux d’Elevage Charolais (2012 and 2014) and Nguyen *et al.* (2012). Mature body weights for Charolais are guesstimate from the many records weights. Brahman cattle can vary considerably in mature body weight. (Nguyen *et al.*, 2012)

o Estimated from the age at first parturition. (Réseaux d’Élevage Charolais, 2012 and 2014)

p Guesstimate.

***Table S3***. Constituents and characteristics of various feed types consumed by beef cattle, which are used as input for the feed intake and digestion sub-model. Constituents are expressed in g kg-1 DM. Digestion and passage rates are expressed as the fraction of DM digested per hour. These parameters are found in section 1.3.2 of the R-code. Abbreviations in the table and R-code are the same.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Feed type | SNSC | INSC | DNDF | UNDF | SCP | DCP | UCP | kdINSC | kdDNDF | kdDCP | kPass | FU1 | peNDF2 |
| Barley3 | 389 | 214 | 156 | 17.3 | 34.5 | 48.0 | 20.7 | 0.242 | 0.145 | 0.125 | 0.040 | 0.573 | 0.70 |
| Concentrates3 | 262 | 175 | 243 | 42.9 | 72.8 | 87.4 | 21.8 | 0.150 | 0.060 | 0.100 | 0.040 | 0.619 | 0.70a |
| Hay (good quality)3 | 100 | 150 | 346 | 148.2 | 48.2 | 74.3 | 49.5 | 0.300 | 0.040 | 0.085 | 0.035 | 1.120 | 1.00 |
| Hay (poor quality)4,6 | 73b | 73b | 462b | 198.0 | 20.3 | 28.0b | 21.7b | 0.300 | 0.040 | 0.085 | 0.035 | 1.370 | 1.00 |
| Grass (spring)4,6 | 130 | 30c | 360d | 40.0 | 66.3 | 149.1e | 49.7 | 0.300 | 0.040 | 0.085 | 0.035 | 0.960 | 0.40f |
| Grass (summer)4,6 | 100 | 60c | 376d | 94.0 | 49.5 | 97.9e | 32.6 | 0.300 | 0.040 | 0.085 | 0.035 | 1.120 | 0.70f |
| Grass (dry summer)4,6 | 50 | 60c | 410d | 175.5 | 23.0 | 69.0e | 23.0 | 0.300 | 0.040 | 0.085 | 0.035 | 1.280 | 1.00f |
| Maize grain3 | 202 | 532 | 102 | 11.3 | 20.1 | 86.6 | 27.4 | 0.040 | 0.051 | 0.035 | 0.050 | 0.438 | 0.40 |
| Maize silage3 | 100 | 351g | 239 | 239.0 | 54.9 | 23.0 | 4.0 | 0.250 | 0.040 | 0.040 | 0.030 | 1.000 | 0.93 |
| Molasses4 | 828 | 0 | 0h | 0.0 | 3.8 | 0.2 | 0.0 | - | - | 0.125i | 0.040i | 0.675 | 0.00h |
| Soy bean meal5 | 107 | 90j | 139k | 0.0 | 202.8l | 243.4l | 60.8l | 0.242 | 0.145 | 0.125i | 0.040i | 0.526 | 0.40 |
| Straw (cereals)5,6 | 14 | 78j | 401m | 0.0 | 10.0 | 5.0 | 25.0 | 0.300 | 0.040 | 0.085 | 0.035 | 1.800 | 1.00n |
| Wheat3 | 475 | 212 | 80 | 34.2 | 39.9 | 69.8 | 23.3 | 0.182 | 0.150 | 0.080 | 0.040 | 0.475 | 0.70 a |

SNSC = Soluble, non-structural carbohydrates; INSC = Insoluble, non-structural carbohydrates; DNDF = digestible neutral detergent fibre; UNDF = undegradable neutral detergent fibre; SCP = soluble crude protein; DCP = digestible crude protein; UCP = undegradable crude protein; kdINSC = digestion rate insoluble, non-structural carbohydrates, kdDNDF = digestion rate digestible neutral detergent fibre; kdDCP = digestion rate digestible crude protein; kPass = passage rate; FU = fill units, peNDF = physical effectiveness factor (for neutral detergent fibre).

1 FU obtained from Jarrige (1989). FUs for barley, concentrates, maize, soybean meal, and wheat are calculated as -2.276 × digestible DM (g kg-1) + 2.545.

2 Data from Mertens (1997). (Jarrige, 1989, Mertens, 1997)

3 Chilibroste *et al.* (1997) (Chilibroste *et al.*, 1997)

4 Kolver (2000) (Kolver, 2000)

5 MAFF (1986) (MAFF, 1986)

6 Digestion and passage fractions of these feed types are assumed to be equal to good quality hay.

a The peNDF of concentrates and wheat is assumed to be equal to the peNDF of barley.

b Ratio SNSC : INSC, DNDF : NDF, and DCP : UCP for poor quality hay are adopted from Chilibroste *et al.* (1997).

c INSC assumed to be equal to the starch content of these feeds.

d DNF assumed to be 90%, 80%, and 70% of NDF for spring, summer, and dry summer.

e The ratio DCP : UCP is assumed to be 3 : 1.

f Guesstimates

g Value adopted from Kolver (2000), as the INSC content given in Chilibroste *et al.* (1997) was relatively low (100 g kg-1 DM).

h The peNDF of molasses is assumed to be zero, since molasses do not contain NDF.

i Values assumed to be equal to kdDCP and kPass of barley.

j Values indicate the starch content of soybean and wheat straw from Kolver (2000).

k 90% of NDF is assumed to be degradable.

l Proportions SCP, DCP, and UCP relative to CP are assumed to be similar to concentrates.

m DNDF is assumed to be 50% of NDF.

n Assumed to be similar to good and poor quality hay.

***Table S4*.** Heat increment of feeding of feed types consumed by beef cattle, calculated from Chandler (1994). Feed types correspond to the feed types in Table S3. The parameter for heat increment of feeding are found in section 1.3.2 of the R-code.

|  |  |
| --- | --- |
| Feed type | HIF1 |
| Barley | 0.245 |
| Concentrates | 0.249 |
| Hay (good quality) | 0.318 |
| Hay (poor quality) | 0.421 |
| Grass (spring) | 0.304 |
| Grass (summer) | 0.356 |
| Grass (dry summer) | 0.447 |
| Maize grain | 0.237 |
| Maize silage | 0.290 |
| Molasses 2 | 0.050 |
| Soybean meal | 0.242 |
| Straw (cereals) | 0.557 |
| Wheat | 0.239 |

HIF = heat increment of feeding (MJ MJ-1 ME).

1 Calculated from Chandler (1994). Heat production in kJ per MJ NE for lactation = 1350.812 -17.1496 × D + 0.091517 × D2, where D is the digestibility of the feed (g kg-1 DM). (Chandler, 1994)

2 Molasses are assumed to have a significantly lower HIF than calculated from Chandler (1994).

***Table S5.*** Physical and chemical parameters used as input for the sub-models of LiGAPS-Beef to simulate beef cattle.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| # | Parameters | Value | Unit(s) | Sub-model1 | Name R-code2 |
| Physical parameters | |  |  |  |  |
| 1 | Absolute zero temperature | -273.15 | °C | T | CtoK |
| 2 | Conversion factor °K to °Ra | 1.8 |  | T | KtoR |
| 3 | Conversion factor kJ day-1 to W | 86.4 |  | T | kJdaytoW |
| 4 | Conversion factor s m-1 to W m-2 K-1 b | 7.8 × 10-4 |  | T | RUC |
| 5 | Emissivity factorc | 0.98 |  | T | EMISS |
| 6 | Gravitational constant | 9.81 | m s-2 | T | GRAV |
| 7 | Latent heat of water vapour | 2260 | kJ kg-1 | T | L |
| 8 | Psychometric constant | 66 | Pa K-1 | T | GAMMA |
| 9 | Reference temperature aird | 524 | °R | T | TR0 |
| 10 | Reflectance vegetatione | 0.1 |  | T | REFLEgrass |
| 11 | Schmidt numberf | 0.61 |  | T | Schmidt |
| 12 | Specific gas constant water vapour | 461.5 | J kg-1 K-1 | T | Rwater |
| 13 | Specific heat of air | 1.005 | kJ kg-1 K-1 | T | Cp |
| 14 | Standard air pressure | 101325 | Pa | T | P |
| 15 | Standard air viscosity | 1.827 × 10-5 | N s-1 m-2 | T | MuSt |
| 16 | Stefan-Boltzmann constant | 5.670 × 10-8 | W m-2 K-4 | T | SIGMA |
| 17 | Sutherlands constant in standard air | 120 |  | T | ST |
| 18 | Universal gas constant | 287.058 | J kg-1 K-1 | T | Rdair |
| 19 | Conversion factor calories to Joules | 4.184 |  | E | CALTOJOULE |
| Chemical parameters | |  |  |  |  |
| 20 | Conversion nitrogen (N) to crude protein | 6.25 |  | E | NtoCP |
| 21 | Gross energy carbohydrates | 17.4 | kJ g-1 | D | GECARB |
| 22 | Gross energy feedsg | 18.5 | kJ g-1 | D | GEFEED |
| 23 | Gross energy lipidh | 39.6 | kJ g-1 | D,E | GELIPID |
| 24 | Gross energy proteinh | 23.8 | kJ g-1 | D,E | GEPROT |

1 T = thermoregulation sub-model; D = feed digestion sub-model; E = energy and protein utilisation sub-model.

2 Parameter names in the R-code.

a K = Kelvin; R = Rankine

b Calculated from Cena and Clark (1978) (Cena and Clark, 1978)

c Assumed to be applicable to the coat of beef cattle and the animals’ surrounding.

d Reference temperature is required to calculate air viscosity.

e Reflectance of solar radiation for vegetation (grass). This value is assumed to be 0.50 for concrete in feedlots without an roof.

f The Schmidt number is assumed to be constant at low water vapour concentrations.

g Feed composition can affect GE content, but in the model, GE content of feed is a constant. This parameter is estimated from MAFF (1986).

h Emmans (1994) (Emmans, 1994)

***Table S6.*** Universal biological parameters for cattle and feed. Breed-specific parameters of cattle are given in Table S2.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| # | Parameter | Value | Unit(s)1 | Reference | Sub-model2 | Name R-code3 |
| 1 | Basal respiration rate 1 | 73.8 | min-1 | McGovern and Bruce, (2000) | T | BASALRR1 |
| 2 | Basal respiration rate 2 | -0.286 |  | McGovern and Bruce, (2000) | T | BASALRR2 |
| 3 | Basal tidal volume | 0.0117 | L min-1 | McGovern and Bruce, (2000) | T | BASALTV |
| 4 | Body area 1 | 0.14 | m-2 | Thompson *et al.* (2011b) | T | BODYAREA1 |
| 5 | Body area 2 | 0.57 | m-2 | Thompson *et al.* (2011b) | T | BODYAREA2 |
| 6 | Body diameter 1 | 0.06 | m | McGovern and Bruce (2000) | T | DIAMETER1 |
| 7 | Body diameter 2 | 0.39 | m | McGovern and Bruce (2000) | T | DIAMETER2 |
| 8 | Body temperature | 39 | °C | McGovern and Bruce (2000) | T | TbodyC |
| 9 | Coat constant | 1.9 × 10-5 | m | McGovern and Bruce, 2000 | T | CoatConst |
| 10 | Coat resistance | 11000 | s m-2 | McGovern and Bruce (2000) | T | ZC |
| 11 | Evaporation rain from coat | 0.15 |  | Guesstimate | T | RAINEVAP1 |
| 12 | Exhaled temperature 1 | 17 | °C | Stevens (1981) | T | TEXHALED1 |
| 13 | Exhaled temperature 2 | 0.3 |  | Stevens (1981) | T | TEXHALED2 |
| 14 | Exhaled temperature 3 | 0.01611 |  | Stevens (1981) | T | TEXHALED3 |
| 15 | Exhaled temperature 4 | 0.0387 |  | Stevens (1981) | T | TEXHALED4 |
| 16 | Fraction animal area exposed to rain | 0.5 |  | Assumption | T | RAINEXP |
| 17 | Fraction animal area to vegetation | 0.5 |  | Assumption | T | FRACVEG |
| 18 | Maximum respiration increase | 7.64 |  | Calculated from McGovern and Bruce (2000) | T | RESPINCR |
| 19 | Min. conductance core-skin 1 | 0.03 | W m-2 K-1 | McGovern and Bruce (2000) | T | MINCCS1 |
| 20 | Min. conductance core-skin 2 | 0.33 | kg-1 TBW | McGovern and Bruce (2000) | T | MINCCS2 |
| 21 | Minimum latent heat release skin | 10 | W m-2 | Turnpenny *et al.* (2000a) and Turnpenny *et al.* (2000b) | T | LASMIN |
| 22 | Reduction in resistance due to rain | 0.30 |  | Mount and Brown (1982) | T | RAINFRAC |
| 23 | Respiration duration | 0.25 |  | Calibration | T | RESPDUR |
| 24 | Lucas equation, slope | 0.9 |  | Lucas *et al.* (1961) | D | LUCAS1 |
| 25 | Lucas equation, intercept | 32 | g kg-1 | Lucas *et al.* (1961) | D | LUCAS2 |
| 26 | DE to ME conversion | 0.82 |  | NRC (2000) | D | DETOME |
| 27 | Maximum digestion capacity | 0.123 | FU kg-0.75 TBW | Estimated from Jarrige *et al.* (1986) | D | PHFEEDCAP |
| 28 | Passage rate DNDF | 0.125 |  | Cabral *et al.* (2011) | D | NDFPASS |
| 29 | Rumen development 1 | 7.246 × 10-3 |  | Assumption: rumen functioning develops in 138 days | D | RUMENDEV1 |
| 30 | Rumen development 2 | 0.10145 |  | Assumption: no feed intake in first 14 days. | D | RUMENDEV2 |
| 31 | Total tract digestibility INSC | 0.97 |  | Moharrery *et al.* (2014) | D | TTDIGINSC |
| 32 | Total tract DNDF digestibility | 0.9 |  | Cabral *et al.* (2011) | D | NDFDIGEST |
| 33 | Bone growth 1 | 0.6436 | kg | Estimated from Berg and Butterfield (1968) | E | BONEGROWTH1 |
| 34 | Bone growth 2 | 0.262 | kg | Estimated from Berg and Butterfield (1968) | E | BONEGROWTH2 |
| 35 | (Initial) carcass fraction at birth | 0.50 |  | Estimated from Fox *et al.* (1976) | E | INCARC |
| 36 | Compensatory growth fat tissue | 0.8 |  | Calibration | E | FATTISCOMP |
| 37 | Conversion foetus to total conceptaa | 1.667 |  | Jarrige *et al.* (1986) | E | FtoConcW |
| 38 | CP for gestation | 4.322 | g CP MJ‑1 NE | CSIRO (2007) | E | CPGEST |
| 39 | Dermal loss protein | 0.11 | g kg-0.75 EBWb | CSIRO (2007) | E | DERMPL |
| 40 | Digestibility milk | 0.95 |  | Guilloteau *et al.* (1986) | E | MILKDIG |
| 41 | Efficiency of fat tissue dissimilation | 0.9 |  | Guesstimate | E | DISSEFF |
| 42 | Energy partitioning non-carcass 1 | 0.6 |  | Calibration | E | ENNONC1 |
| 43 | Energy partitioning non-carcass 2 | 0.03 |  | Calibration | E | ENNONC2 |
| 44 | Factor for compensatory growth | 4 |  | Assumption | E | COMPFACT |
| 45 | Factor for fat accretion | 0.065 |  | Assumption | E | FATFACTOR |
| 46 | Fraction lipid in fat tissue | 0.7 |  | Estimated from Thonney (2014) | E | LIPFRACFAT |
| 47 | Fraction lipid in muscle tissue | 0.005 |  | Warren *et al.* (2008) | E | LIPFRACMUSCLE |
| 48 | Fraction protein in bone tissue | 0.23 |  | Field *et al.* (1974) | E | PROTFRACBONE |
| 49 | Fraction protein in fat tissue | 0.08 |  | Estimated from Thonney (2014) | E | PROTFRACFAT |
| 50 | Fraction protein in milkb | 0.04 |  | Moe and Tyrrell (1975) | E | PROTFRACMILK |
| 51 | Fraction protein in muscle tissue | 0.21 |  | Coşuleanu *et al.* (2010) | E | PROTFRACMUSCLE |
| 52 | Fraction rumen in TBW | 0.10 |  | Assumption | E | RUMENFRAC |
| 53 | Gestation period | 286 | days | Blanc and Agabriel (2008) | E | GestPer |
| 54 | Gross energy milk 1 | 5.5109 | kJ L-1 | Based on Restle *et al.* (2003) | E | GEMILK1 |
| 55 | Gross energy milk 2 | 2589 | kJ L-1 | Based on Restle *et al.* (2003) | E | GEMILK2 |
| 56 | Intra-muscular growth 1 | 1.0  ×10-4 |  | Estimated from Berg and Butterfield (1976) | E | IMFGROWTH1 |
| 57 | Intra-muscular growth 2 | 0.01 |  | Estimated from Berg and Butterfield (1976) | E | IMFGROWTH2 |
| 58 | Intra-muscular growth 3 | 0.04 |  | Estimated from Berg and Butterfield (1976) | E | IMFGROWTH3 |
| 59 | Lipid fraction bone 1 | 0.075 |  | Estimated from data of Field *et al.* (1974) | E | LIPBONE1 |
| 60 | Lipid fraction bone 2 | 3.0496 |  | Estimated from data of Field *et al.* (1974) | E | LIPBONE2 |
| 61 | Lipid fraction bone 3 | 3.3268 |  | Estimated from data of Field *et al.* (1974) | E | LIPBONE3 |
| 62 | Lipid fraction non-carcassc |  |  | Guesstimate | E | LIPNONC1 – LIPNONC4 |
| 63 | Maximum compensatory growth | 1.2 |  | Guesstimate | E | COMPFACTTIS |
| 64 | Maximum fraction bones in carcass | 0.25 |  | Estimated from Berg and Butterfield (1976) | E | BONEFRACMAX |
| 65 | Maximum fraction lipid accr. carcass | 0.8 |  | Assumption | E | LIPNONCMAX |
| 66 | Minimum calving interval | 365 | days | Assumption | E | GESTINTERVAL |
| 67 | Minimum fraction lipid accr. carcass | 0.15 |  | Assumption | E | LIPNONCMIN |
| 68 | Muscle growth 1 | -2.0 × 10-5 |  | Estimated from Berg and Butterfield (1976) | E | MUSCLEGROWTH1 |
| 69 | Muscle growth 2 | 1.564 |  | Estimated from Berg and Butterfield (1976) | E | MUSCLEGROWTH2 |
| 70 | N recycling 1 | 121.7 |  | Russell *et al.* (1992) | E | NRECYCL1 |
| 71 | N recycling 2 | 12.01 |  | Russell *et al.* (1992) | E | NRECYCL2 |
| 72 | N recycling 3 | 0.3235 |  | Russell *et al.* (1992) | E | NRECYCL3 |
| 73 | NE efficiency for gestation (incl. concepta) | 0.234 | MJ NE MJ-1 NE | Calculated from Jarrige (1989) and Ratray *et al.* (1974) | E | NEIEFFGEST |
| 74 | NE efficiency for milk production | 0.85 | MJ NE MJ-1 NE | Calculated from Moe and Tyrrell, (1975) and Restle *et al.* (2003) | E | NEEFFMILK |
| 75 | NE efficiency lipid accretion | 0.74 | MJ NE MJ-1 NE | Trottier (2016) | E | LIPIDEFF |
| 76 | NE efficiency protein accretion | 0.54 | MJ NE MJ-1 NE | Trottier (2016) | E | PROTEFF |
| 77 | NE for gestation requirementsd |  | MJ NE day-1 | Fox *et al.* (1988) | E | NEREQGEST |
| 78 | NE for maintenance *B. taurus* cattle | 311 | kJ kg-0.75 EBW3 | Ouellet *et al.* (1998) | E | NEm |
| 79 | NE for physical activitye | 70 | kJ kg-0.75 EBW3 | CSIRO (2007) | E | NEpha |
| 80 | Max. protein content non-carcass 1 | -7.014 × 10-3 |  | Estimated from Berg and Butterfield (1976) | E | PROTNONCM1 |
| 81 | Max. protein content non-carcass 2 | 20.4 |  | Estimated from Berg and Butterfield (1976) | E | PROTNONCM2 |
| 82 | Protein efficiency for milk production | 0.68 |  | CSIRO (2007) | E | PROTEFFMILK |
| 83 | Protein fraction non-carcass 1 | 8.7492 × 10-10 |  | Estimated from Berg and Butterfield (1976) | E | PROTNONC1 |
| 84 | Protein fraction non-carcass 2 | 9.0732 × 10-7 |  | Estimated from Berg and Butterfield (1976) | E | PROTNONC2 |
| 85 | Protein fraction non-carcass 3 | 3.3117 × 10-4 |  | Estimated from Berg and Butterfield (1976) | E | PROTNONC3 |
| 86 | Protein fraction non-carcass 4 | 0.061756 |  | Estimated from Berg and Butterfield (1976) | E | PROTNONC4 |
| 87 | Protein fraction non-carcass 5 | 22.26 |  | Estimated from Berg and Butterfield (1976) | E | PROTNONC5 |
| 88 | Protein requirement per unit NE | 0.478 | g MJ-1 | CSIRO (2007) | E | PROTNE |
| 89 | Weaning period | 210 | days | Jenkins and Ferrell (1992) | E | WEANINGTIME |

CP = crude protein; DE = digestible energy; DNDF = digestible neutral detergent fibre; EBW = empty body weight; INSC = insoluble, non-structural carbohydrates; ME = metabolisable energy; N = nitrogen; NE = net energy; TBW = total body weight

1 If no unit is given, the parameter is dimensionless. Sometimes dimensionless parameters are given with units (*e.g.* MJ NE MJ-1 NE).

2 T = thermoregulation sub-model; D = feed digestion sub-model; E = energy and protein utilisation sub-model.

3 Name used in the R-code.

a The weight of the foetus is multiplied by 1.667 to calculate the total weight increase of a cow due to gestation, including the concepta.

b Value for fat-corrected milk.

c This is listed here as a parameter, but the lipid fraction in the non-carcass tissue is determined by an empirical formula with many parameters, which are not provided in this table.

d This is listed as a parameter here, but the NE for gestation is determined by a formula with many parameters given in Fox *et al.* (1988), which are not provided in this table. The variable for NE for gestation is NEREQGEST in the R-code. (Fox *et al.*, 1988)

e This parameter is assumed to be a constant, but it is variable in practice, depending on the amount of energy spent by cattle on grazing and locomotion.

1.2 Thermoregulation sub-model

Metabolisable energy (ME) for metabolic processes is partly converted into heat. Cattle are isothermal animals with a body temperature, Tb, of approximately 39°C (Turnpenny *et al.*, 2000b). Although hot conditions can increase cattle body temperatures for a few hours (West, 2003, Parkhurst, 2010), a constant Tb is assumed, as LiGAPS-Beef has a daily time step. A constant Tb implies that daily heat production from metabolic processes must equal daily heat release from the body. Daily heat production is an input for the thermoregulation sub-model from the energy and protein utilisation sub-model.

The thermoregulation sub-model is based on cattle thermoregulation models of McGovern and Bruce (2000) and Turnpenny et al. (2000a). These models consider an animal as a cylinder consisting of three layers: body core, skin, and coat. Metabolic processes generate heat, Hmet, in the body core and solar radiation, HSWR, heats the coat also. Heat is lost from the body core via respiration, Hresp, and from the skin via latent heat release (sweating), HLHR. Part of the solar radiation is reflected from the coat, Hrefl. Heat is lost also from the coat through convection, Hconv, long wave radiation (LWR), HLWR, and evaporation of rainwater, Hrain. The sum of heat inputs equals the sum of heat outputs for isothermal animals (Eq. 1) Hmet is the balancing variable in the thermoregulation sub-model (Eq. 1).

Daily weather data required to calculate daily heat release are solar radiation, minimum and maximum temperature, vapour pressure, wind speed, precipitation, a factor converting solar radiation at a horizontal surface to solar radiation at an animal’s coat, and cloud cover (Table S1). The latter two can be derived from the other weather data, as demonstrated in Appendix I. Weather data from meteorological stations are assumed to represent the climate for outdoor conditions. If animals are housed in open stables, the outdoor temperature can be converted to indoor temperature via empirical equations. Likewise, the indoor wind speed can be calculated from the outdoor wind speed, based on the construction of the stable. In addition, solar radiation can be set to zero if the stable is equipped with a non-transparent roof. Indoor climate data are applicable if animals are housed in closed stables, although this is rare in cattle husbandry.

Cattle regulate heat release by three mechanisms: vasoconstriction or vasodilatation; latent heat release from the skin (sweating); and panting. Minimum heat release is realised with maximum vasoconstriction, minimum latent heat release from the skin, and without panting. Maximum heat release is realised with maximum vasodilatation (*i.e.* minimum vasoconstriction), maximum latent heat release from the skin, and maximum panting. The thermoregulation sub-model calculates both minimum and maximum heat release. An animal is within the thermoneutral zone (TNZ), if heat production from metabolic processes (and solar radiation on the coat) is between minimum and maximum heat release. An animal is below the TNZ if heat production is lower than the minimum heat release. An animal has to generate more heat to prevent hypothermia below the TNZ, either by increasing feed intake, by using energy for heat production, or by dissimilation of body fat. This situation is referred to as ‘cold stress’, which can be a defining factor for growth. If an animal is below the TNZ, and if it can increase feed intake to compensate for the effects of cold stress, its growth rate is not affected, but its feed efficiency (FE, expressed in g beef kg-1 DM feed) decreases. If and animal is below the TNZ, and if it cannot compensate for the effects of cold stress by an increased feed intake, the animals either have to use energy for heat production or have to dissimilate body fat. Using energy for heat generation reduces energy available for growth, and subsequently cold stress reduces growth in this particular situation. If feed intake is at sub-maintenance level, body fat reserves have to be dissimilated to provide additional energy. Hence, if cold stress cannot be compensated sufficiently by an increase feed intake, both animal growth and FE are reduced.

If heat production is higher than the maximum heat release, the animal is above the TNZ, and the animal has to reduce its feed intake to prevent hyperthermia. This situation is referred to as ‘heat stress’, which is a defining factor for growth. Heat stress reduces growth and FE. The occurrence of cold stress and heat stress is input for the feed intake and digestion sub-model.

The ability to release heat differs among cattle breeds, because of differences in reflection of sunlight on the coat (Da Silva *et al.*, 2003), physiological limits for latent heat release via the skin (McGovern and Bruce, 2000), and body area per kg total body weight (TBW). The body area of *B. indicus* cattle is 12% larger than *B. taurus* cattle at the same weight (Johnston *et al.*, 1958). The area of *B. taurus* cattle, Aa, is assumed to be a function of TBW (Thompson *et al.*, 2011b) (Eq. 2). Animal diameter, Ad, is assumed to be a function of TBW as well (McGovern and Bruce, 2000) (Eq. 3).

[S6, 4-5]

[S6, 6-7]

*Interception and reflection of solar radiation*

Solar radiation is assumed to be short wave radiation (SWR) only. The heat load from SWR, HSWR, consists of SWR from the sky and SWR reflected by the underground, which can be the vegetation or the concrete floor of a feedlot (Eq. 4) (McGovern and Bruce, 2000, Turnpenny *et al.*, 2000a).

[S2, 5; S5, 10]

Where η is the albedo of the animals’ coat, and ηu is the albedo of the underground. A value of 0.10 is assumed for grassland vegetation. The albedo of the coat is dependent on coat colour (Finch, 1986, Brown-Brandl *et al.*, 2006). Meteorological stations generally record daily solar radiation per m2 horizontal soil surface. The conversion of solar radiation per m2 soil to solar radiation per m2 coat is given in the Appendix I.

*Respiration*

Air exchange between the respiratory system in the body core and the environment occurs at a basal rate under climate conditions below and in the TNZ. The basal air volume exchanged daily, AVb, is required to calculate heat release via respiration (Eq. 5) (McGovern and Bruce, 2000).

[S6, 1-3]

Where 1.44 is a conversion factor from L min-1 to m3 day-1. Under climate conditions above the TNZ, an animal increases the exchange of air via panting. The maximum volume of air exchanged by the animal, AVm, is calculated from McGovern and Bruce (2000), assuming that an animal reduces its feed intake when panting occurs longer than six hours per day (Eq. 6).

[S6, 18]

The temperature of the exhaled air, Texh, is a function of the inhaled air temperature, Tair, and relative humidity of the air, RHair (Stevens, 1981) (Eq. 7). It is assumed that exhaled air is saturated with water vapour, so its relative humidity is 100%.

[S6, 12-15]

The gross heat release by respiration, Hgres, is calculated according to McGovern and Bruce (2000), and includes heat release via convection and latent heat release (Eq. 8).

[S2, 7,13]

Where AV is the exchanged air volume, either at basal level (AVb) or the maximum level (AVm), ρair is the air density, Cair is the specific heat of air, λ is the latent heat of water vapour, χexh is the water vapour density of exhaled air, and χair is the water vapour density of inhaled air. Cair is assumed to be a constant of 1.005 kJ kg-1 K-1. The net energy (NE) requirements for basal respiration are assumed to be included in the NErequirements for maintenance, but panting under heat stress requires additional energy, NEresp (McGovern and Bruce, 2000). Additional NEres is calculated for the six hours of with maximum air exchange (Eq. 9). The net heat release from panting, Hres, equals Hgres minus NEres.

The minimum conductivity between body core and skin corresponds to maximum vasoconstriction, which occurs under conditions below the TNZ. Maximum conductivity between body core and skin corresponds to maximum vasodilatation, which occurs under conditions above the TNZ. Minimum conductivity between body core and skin, Cbsmin, is adopted from McGovern and Bruce (2000) (Eq. 10).

[S2, 4; S6, 19,20]

Where C is a breed specific constant, which is assumed to be equal to 1 for *B. taurus* cattle, and 1.3 for *B. indicus* cattle (Table S2). Maximum conduction between body core and skin is assumed to be 64 W m-2 K-1 for all cattle breeds (Turnpenny *et al.*, 2000a). The conduction between body core and skin enables to calculate skin temperature, Ts (Eq. 11).

[S2, 2]

Where Cbs is the minimum or maximum conduction between body core and skin.

*Latent heat release from the skin*

The minimum release of latent heat from the skin, HLHRmin, is assumed to be 10 W m-2 coat, which is equivalent to 0.864 MJ m-2 coat day-1 (Turnpenny *et al.*, 2000a, Turnpenny *et al.*, 2000b). Maximum release of latent heat from the skin, HLHRmax, is determined by either the maximum physiological capacity for latent heat release, HLHRphys, or the scope for latent heat release by the environment, HLHRenv. HLHRphys is assumed to be dependent on the skin temperature, Ts (Eq. 12) (Da Silva and Maia, 2011, Thompson *et al.*, 2011a).

[S2, 6-8; S6, 21]

Where SA,SB, and SC are empirical parameters specific for *B. taurus* and *B. indicus* cattle, which are calculated from experiments of Schleger and Turner (1964) and Gatenby (1986). HLHRenv is calculated based on Thompson *et al.* (2011b) (Eq. 13).

[S5, 8,13]

Where γ is the psychrometric constant, esskin is the saturated water vapour pressure of air, eair is the water vapour pressure and Rvp is the resistance to vapour transfer. Rvp is calculated according to Thompson *et al.* (2011b) and Turnpenny et al. (2000a). Conduction of heat between skin and coat, Csc, is dependent on coat length (Turnpenny *et al.*, 2000a) (Eq. 14), and is corrected for precipitation. Conduction of heat between skin and coat increases linearly with increasing precipitation. Conduction increases by with an increasing levels of precipitation (Mount and Brown, 1982).

[S2, 3; S5, 4; S6, 10]

Where ZC is the coat resistance, CL is the coat length, and DCL is the reduction in coat length due to wind. DLC is calculated from McGovern and Bruce (2000). Calculating Csc, including the effect of precipitation, enables to calculate coat temperature, Tc (Eq. 15).

Where HLHR is either minimum or the maximum heat release from the skin.

*Convection*

Heat release via convection from the skin, Hconv, is calculated from the thermal conductivity of air, ka, the Nusselt number, Nu, animal diameter, Ad, and the difference between Tc and Ta (Eq. 16).

Where Tc is the coat temperature and Ta is the average daily air temperature. Nu is calculated according to Turnpenny et al. (2000a), and ka was calculated using an empirical formula (Eq. 17), in which coat temperature is expressed in °K. Heat release via convection increases with precipitation, just as the conduction from skin to coat.

*Long wave radiation*

Calculations on heat release via long wave radiation (LWR), HLWR, follow McGovern and Bruce (2000) (Eq. 18). Ta is used to calculate LWR from the environment, HLWR env., and Tc is used to calculate LWR from the coat, HLWR coat.

[S5, 5]

Where ε is the emissivity factor and HLWR sky. is the LWR from the sky. HLWR sky is calculated from McGovern and Bruce (2000) and the Idso-Jackson formula, which calculates LWR from a clear sky (Eq. 19). Temperatures in Eqs 18 and 19 are in °K. Cloud cover, Ω, may not be available for specific locations. The method to compute Ω from solar radiation is given in Appendix I. HLWR env is calculated based on Ta, and HLWR coat based on Tc.

[S5, 16]

*Evaporation of rainwater*

Being exposed to precipitation affects the heat balance of an animal (Turnpenny *et al.*, 2000a). Rainwater is assumed to be partly evaporated, Hrain. This pathway for latent heat release from the coat cools the animal.

[S5, 7; S6, 11]

Where L is the length of the animal cylinder, prec. is the precipitation in mm per day, and λ is the latent heat of evaporation of water. For simplicity, we assume that 15% of the rainwater is evaporated.

*Calculation of minimum and maximum heat release*

The thermoregulation sub-model balances heat inputs and outputs (Eq. 1). It starts with a guesstimate for Hmet, which gives a specific heat output. If heat input and heat output are not similar after this calculation, Hmet is adapted again. This procedure is used to calculate the minimum heat release corresponding to the lower critical temperature (LCT) and the maximum heat release corresponding to the upper critical temperature (UCT). If Hmet is lower than heat output while calculating the LCT, Hmet is increased by 5%, whereas if Hmet is higher than heat output, Hmet is decreased by 5%. If Hmet is lower than heat output while calculating the UCT, Hmet is increased by 10%, whereas if Hmet is higher than heat output, Hmet is decreased by 10%. This procedure is repeated until heat input and output are equal. The procedure is conducted for both minimum heat release and maximum heat release. The output of the thermoregulation sub-model is subsequently the minimum and maximum heat release, in W m-2 coat. The environmental temperature that corresponds to the minimum heat release is the lower critical temperature (LCT). Likewise the environmental temperature that corresponds to the maximum heat release is the upper critical temperature (UCT).

## 1.3 Feed intake and digestion sub-model

The feed intake and digestion sub-model of LiGAPS-Beef is essential to simulate growth and production of cattle under limited feed quality and feed quantity. Inputs for this sub-model are feed types and the available feed quantity at a daily basis. Feed availability can be set *ad libitum* in LiGAPS-Beef to simulate potential or feed quality limited production. Feed characteristics of specific feed types are found in tables S3 and S4. The main outputs of the feed intake and digestion sub-model are ME and digested protein.

*Maximum feed intake and digestion capacity*

Cattle have a maximum capacity to digest specific feed types. The INRA fill unit system was adopted to calculate the maximum digestion capacity of the rumen and the rumen fill (Jarrige *et al.*, 1986, Jarrige, 1989, Faverdin *et al.*, 2011). One kg DM of a reference pasture grass has a fill value (FU) equal to one. Other feeds have FUs relative to the reference pasture grass. FUs are listed for many feed types (Jarrige *et al.*, 1989), but are missing for others (*e.g.* barley, maize grain, concentrates, molasses, soy bean meal, and wheat). Missing FUs were calculated using linear regression between average feed digestibility and available FUs for seven different feed types (Eq. 21). The seven feed types included in simple linear regression were grass in spring, summer, and a dry summer, good and poor quality hay, cereal straw, and maize silage (Table S3).

Where FU is fill units kg-1 DM and Fdig is the digestibility of the feed (kg kg-1 DM). The maximum amount of FUs in the digestive tract, FUmax, is assumed to be proportional to the metabolic body weight. Maximum fill value for cattle varies between 0.07-0.14 FU kg-0.75 empty body weight (EBW) (Jarrige *et al.*, 1986). A maximum fill value of 0.123 FU kg-0.75 TBW was adopted in the feed intake and digestion sub-model. Rumen fill, RF, is subsequently calculated from FU related to feed intake and FUmax (Eq. 22). The rumen fill has a minimum value of zero, and a maximum value of one. If the rumen fill equals one, the animal cannot ingest more feed, even if the energy requirements are not met and feed is available.

*Feed digestion in the rumen*

Following the model of Chilibroste *et al.* (1997), feed is divided in seven components (Table S3). The soluble components are the water soluble, non-structural carbohydrates (SNSC), and the water-soluble crude protein (SCP). Digestible components are digestible neutral detergent fibre (DNDF), the water insoluble, non-structural carbohydrates (INSC), and insoluble crude protein (UCP). INSC and DNDF can be converted into water-soluble, non-structural carbohydrates, and the insoluble crude protein can be converted to soluble protein. The indigestible or undegradable components are the undegradable neutral detergent fibre (UNDF) and undegradable crude protein (UCP).

Feed disappears from the rumen via digestion and passage to the intestines. SNSC and SCP are fully taken up in the rumen, whereas UNDF and UCP are not digested at all (Chilibroste *et al.*, 1997). Digestion rates of INSC, DNDF, and DCP are dependent on feed type. Passage rate is similar for all feed components, and is dependent on feed type also. Passage rate is also dependent on rumen fill (Chilibroste *et al.*, 1997). For a rumen fill below 45%, passage rate is multiplied by 0.55. For a rumen fill between 45%-65%, passage rate is multiplied by 0.65, and for a passage rate between 65%-85%, passage rate is multiplied by 0.85. For a rumen fill above 85%, no further multiplication occurs (Chilibroste *et al.*, 1997). The passage rate thus decreases with a decreasing rumen fill, which increases digestibility of feed components. Both digestion and passage are described by first-order reactions. The digested fraction of INSC, DNDF, and DCP can be calculated from digestion and passage rates (Eq. 23).

Where Fdigr is the digested fraction of INSC, DNDF, or DCP of a particular feed type in the rumen, kd is the digestion rate, and kp is the passage rate. Since LiGAPS-Beef has a daily time step, it is assumed that all feed is digested within 24 hours, although this does not necessarily reflect reality.

*Feed digestion in the small and large intestines*

Feed particles that are not digested in the rumen end up in the small and large intestines. SNSC and SCP are fully taken up in the rumen, and hence do not end up in the intestines (Chilibroste *et al.*, 1997). INSC, DNDF, and DCP are partly digested in the rumen, and the remainder ends up in the intestines. UNDF and UCP are not digested in the intestines. It is assumed that INSC mainly consists of starch. Whole-tract digestibility of starch is close to 100% (Moharrery *et al.*, 2014). For this reason, a whole-tract digestibility of 97% was assumed for INSC. The percentage INSC digested in the intestines is thus 97% minus the percentage INSC digested in the rumen.

The DNDF that is not digested in the rumen can be digested further in the intestines. Following Cabral *et al.* (2011), the digestion rate of DNDF in the intestines equals 90% of the digestion rate in the rumen. The passage rate of DNDF for all feed types is set at 12.5% per hour (Cabral *et al.*, 2011). The DNDF digested is calculated with the same first-order equation as the digestion of INSC, DNDF, and DCP in the rumen (Eq. 23). The whole-tract digestibility of crude protein (CP) in cattle (Eq. 24) is calculated according to a Lucas-equation (Lucas *et al.*, 1961, Van Soest, 1994).

[S6 24,25]

Where FCPdig is the fraction digested CP per unit of DM feed, and FCP is the fraction CP per unit of DM feed. CP digested in the intestines is the difference between whole-tract CP digestibility and the sum of SCP and digested DCP in the rumen.

*Feed digestion in the whole digestive tract*

The combustion energy, also referred to as gross energy (GE), is assumed to be 17.4 MJ kg-1 DM for carbohydrates, and 23.8 MJ kg-1 DM for CP (Emmans, 1994). Digestible energy (DE) per kg DM is calculated from the digestion of feed components and the GE contents of carbohydrates and CP (Eq. 25).

[S5, 21, 24]

Where FSNSC, FINSCdig, and FDNDFdig are the fractions SNSC, digested INSC, and digested DNDF per unit of DM feed. The digestibility of a feed type or a diet can be calculated on an energy basis (MJ DE MJ-1 GE), or a DM basis (kg kg-1 DM) in LiGAPS-Beef. Metabolisable energy (ME) is assumed to be 82% of DE for beef cattle (NRC, 2000). Multiplying ME per kg DM by DM intake per day results in the amount of ME available to an animal per day. The main outputs of the feed intake and digestion sub-model, ME and digested protein, are inputs for the energy and protein utilisation sub-model.

*Feed intake*

Feed intake is an output of the model LiGAPS-Beef, and is determined by the interaction between the genotype, climate, feed quality, and available feed quantity. All three sub-models of LiGAPS-Beef can influence feed intake. The model, therefore, includes a loop where the information from the three models is integrated. The loop starts under the assumptions that heat and cold stress are absent, that the feed intake of the animal is high (20 kg DM per head per day), and that the animal is fed above the energy requirements for maintenance. Several steps are taken in the integration loop:

1. The minimum of the available feed quantity, the feed digestion capacity, and the feed intake are calculated. For the first time the loop is run, the feed intake is assumed to be 20 kg DM feed is per head per day.
2. Using the minimum calculated in step 1, and a crude estimate for the rumen fill, the amount of energy and protein from this amount of feed is calculated.
3. If heat stress occurs, the amount of ME and protein for panting is deducted. The initial assumption is that heat stress is zero.
4. The ME and protein remaining after step 3 are deducted by the energy requirements for maintenance, gestation, and lactation, and heat increment of feeding.
5. Growth is the balancing factor in the energy balance of LiGAPS-Beef. After the deduction in step 4, a specific amount of NE for growth remains, which is allocated over the various body tissues, as described in section 1.4 on the energy and protein utilisation sub-model.
6. The heat production from all processes, including growth is calculated. If the heat production is lower than the heat production associated with the LCT, additional energy is required to maintain body temperature.
7. If the NE availability for growth is negative, the animal has to dissimilate its body tissues to maintain its key processes, such as maintenance.
8. Based on the ME requirements, the amount of feed intake is calculated. Subsequently, the fraction rumen fill and the passage rate is calculated according to Chilibroste *et al.* (1997). The information on feed intake, rumen fill, and passage rates is used in the next cycle of the loop.
9. After the preceding steps, the results are checked:
   1. the heat production from metabolic processes does not exceed the maximum heat release simulated with the thermoregulation sub-model
   2. the passage rate in the previous run of the loop should equal the passage rate in the current run of the loop
   3. the number of times the loop is run must at least be three

If these three requirements are met, the integration loop stops. If not, the procedure starts again at step the first step, using the feed intake, rumen fill, and passage rates as input.

*Diet under potential production*

Feed quality and quantity are not affecting potential production (Van de Ven *et al.*, 2003, Van der Linden *et al.*, 2015). It is assumed that the optimum diet for sustaining potential growth in cattle consists of wheat (65%) and long hay (35%) of good quality. Wheat has a high ME content per kg DM, whereas the good quality hay supplies the necessary peNDF in the diet (Table S3). The average peNDF fraction of this diet is 0.22, and the amount of FU is 0.70 per kg DM. Although this diet has a relatively high ME (11.8 MJ kg-1 DM) and CP content (147 g CP kg-1 DM), the diet cannot prevent energy and protein deficiency before weaning, which is a phase where the rumen develops (Van der Linden *et al.*, 2018a). For the sake of simplicity, we consider cattle fed with the 65% wheat-35% hay diet to be under potential production, irrespective of small energy or protein deficiencies in early life stages (Van der Linden *et al.*, 2018a). Feed-limitation occurs when ME or protein requirements are not met. Feed quality limitation occurs if maximum feed intake, expressed in FUs, is reached. Feed quality limitation causes either energy deficiency or protein deficiency, depending on the composition of the diet and the ME and protein requirements of an animal. Still, the primary cause for these deficiencies is the limiting factor feed digestion capacity. Feed quantity limitation occurs if feed availability is lower than the maximum digestion capacity and ME and CP requirements of an animal. Hence, either energy or protein deficiency limits growth under feed quantity limitation (Van der Linden *et al.*, 2018a).

*Diets under feed-limited production*

The diet under feed-limited production corresponds to the actual diet fed to animals in practice. Hence, there are no specific requirements to this diet as under potential production. Model users should note that diets with low amounts of fibres yield results, but such simulations may not be realistic. Under feed-limited production, the fraction physically effective NDF (peNDF) of the total diet should be at least 0.21. Lower fractions of peNDF induce acidosis and hamper good rumen functioning (Mertens, 1997). The fraction of peNDF of feed types is found in Table S3. Metabolic disorders related to rumen malfunctioning are reducing factors. LiGAPS-Beef simulates potential and feed-limited production, and reducing factors can, by definition, not influence these two production levels (Van de Ven *et al.*, 2003, Van der Linden *et al.*, 2015). Hence, the effects of acidosis on growth are not included in LiGAPS-Beef.

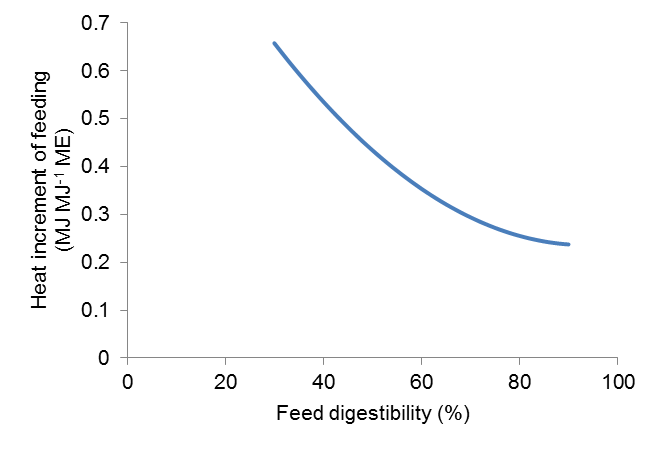
## 1.4 Energy and protein utilisation sub-model

Metabolic processes included in the energy and protein utilisation sub-model are maintenance (fasting maintenance), physical activity, gestation, milk production, growth, and digestion and absorption of feed.

*Conversion from metabolisable energy to net energy*

A conversion is made from metabolisable energy (ME) to net energy (NE). The ME minus heat increment of feeding equals NE (Baldwin *et al.*, 1980). Heat increment of feeding is heat generated by chewing, rumination, digestion, and absorption of feed. Heat increment of feeding is dependent on the feed type (West, 1999). Heat increment of feeding can require up to 70% of the ME for poor-quality feeds (Armstrong and Blaxter, 1956). Heat production for lactating dairy cows is assumed to be a function of digestibility (Chandler, 1994) (Eq. 26).

Where HP is the heat production in kJ MJ-1 ME. The formula given by Chandler (1994) is applicable to NE for lactation. It is assumed that the efficiency for conversion of NE into milk is 85% (calculation in section 1.3.5). The 15% heat production during synthesis of milk components is deducted from the heat production and energy requirements for maintenance 25% of ME) of dairy cattle. This enables to calculate the heat increment of feeding (HIF) in MJ MJ-1 ME (Eq. 27, Fig. S1). Heat increment of feeding of various feed types is listed in table S4.

**

***Figure S1.*** Heat increment of feeding as a function of feed DM digestibility of beef cattle (digestibility between 30 and 90%), based on Eq. 27. ME = metabolisable energy.

*Maintenance*

Maintenance is defined here as fasting maintenance, also referred to as fasting heat production. Maintenance is assumed to be proportional to the metabolic empty body weight (EBW0.75) (Fox *et al.*, 1988). The NE requirement for maintenance, NEm, is assumed to be 311 kJ kg EBW-0.75 day-1 for *Bos taurus* beef cattle (Ouellet *et al.*, 1998) and 280 kJ kg-1 EBW-0.75 day-1 for *Bos indicus* beef cattle (NRC, 2000). NE for maintenance is fully converted into heat. Protein requirements for maintenance consist of dermal losses of protein and protein requirement for fasting maintenance. Dermal losses of protein are 0.11 g CP kg EBW-0.75, and fasting maintenance requires 0.478 g CP MJ-1 NE (CSIRO, 2007). Hence, the CP requirements for maintenance are proportional to the metabolic empty body weight, just like the NE requirements.

*Physical activity*

Physical activity is defined as energy spent on grazing, locomotion, and traction. Physical activity of beef cattle in feedlots and stables is assumed to be negligible. The NE requirement for physical activity, NEpha, are assumed to be 60 kJ kg-1 EBW0.75 day-1 for grazing cattle (Brosh *et al.*, 2006, Brosh *et al.*, 2010). In LiGAPS-Beef we assumed a slightly higher value for physical activity of grazing animals, namely 70 kJ kg-1 EBW0.75 day-1. It should be noted that the NE requirement for physical activity is dependent on many factors, such as weather conditions, the amount of biomass available, species composition, and the quality of forage. LiGAPS-Beef does not simulate crops, so the NE requirements for physical activity are an input for the model. The NE for physical activity is fully converted into heat. The CP requirements for physical activity are 0.478 g CP MJ-1 NE, just as for fasting maintenance (CSIRO, 2007), and proportional to the metabolic body weight. Finally, the NE requirements for physical activity can be written as a function of TBW also in LiGAPS-Beef, as proposed in CSIRO (2007).

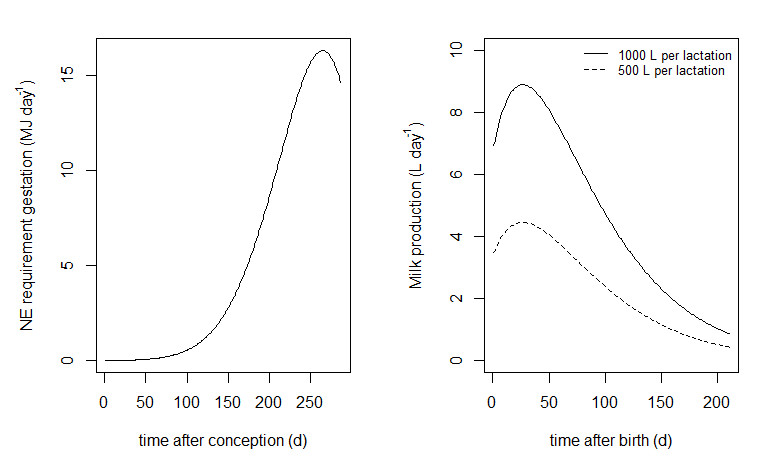
*Gestation*

Gestation occurs after four conditions are met simultaneously. First, cows can conceive if TBW is higher than a minimum fraction of the maximum adult body weight. The minimum fraction is assumed to be 0.60 for *B. taurus* cows and 0.50 for *B. indicus* cows. Second, fat reserves in the carcass have to cover a minimum fraction of the carcass weight, which is set at 0.32 for *B. taurus* cows and 0.20 for *B. indicus* cows. Third, the minimum calving interval is one year (Jouven *et al.*, 2008), and the gestation period is fixed at 286 days (Blanc and Agabriel, 2008) for all breeds. Fourth, cows have to be below a maximum age for conception, which can be specified by the user of the model. The model illustration in the main paper assumed a maximum age of conception of 10 years (Van der Linden *et al.*, 2018a). In addition, the model has an option to set a specific calving date as a fifth condition. This option is applicable to beef production systems that have a short calving season. The specific calving date corresponds to the peak in calving for such a system.

The probability of giving birth to a male or female calf is 50%, and it is assumed that births of twins and triplets do not occur. The standard daily NE requirements (in MJ) for gestation, NEges st, are derived from Fox *et al.* (1988), which are valid for a calf with a ‘standard’ birth weight of 37.2 kg (Eq. 28; Fig. S2).

Where tc is the time after conception, and the addition of 4.18 is the conversion from calories to joules. Furthermore, the efficiency of NE for gestation is assumed to be 14%, excluding the concepta (Jarrige, 1989). The NEges. st covers both growth and maintenance requirements of the foetus and the concepta. It is assumed that NEges. st is proportional to birth weight, which allows to calculate NE requirements for gestation for calves having a different birth weight than the standard birth weight, BW, used in Eq. 28 (Eq. 29).

The weight of the developing calf during gestation is assumed to be proportional to the cumulative amount of NEg, NEgc, over the total amount of NE required for the whole gestation period of 286 days. The weight of concepta is approximately 67% of the birth weight (Jarrige, 1989). It is assumed that weight of concepta equals 67% of the weight of the foetus during the whole gestation period. The efficiency of NE for gestation is thus 23.3% when the concepta are included. Hence, the corresponding heat production is 76.7% of the NE requirements for gestation. Protein requirements for gestation are 4.322 g CP MJ-1 NE (CSIRO, 2007).



*Figure S2.* Net energy (NE) requirement for gestation for a calf with a ‘standard’ birth weight of 36.4 kg. The NE requirements for gestation of cattle are calculated from Fox *et al.* (1988).

*Lactation*

Lactation is assumed to be independent of age and parity under potential production, although this may not be the case for beef cattle (Fox *et al.*, 1988). Variation in NE requirement for lactation among cows of the same breed is assumed to be small compared to energy requirements for other metabolic processes. Hence, a breed-specific curve for lactation (Wood, 1967) is adopted (Eq. 29, Fig. S2).

[S2, 13-15]

Where Milk is the milk production, tp is time after parturition in days, and A, B, and C are breed-specific parameters for the lactation curve, which are obtained after fitting Eq. 30 to milk production data of specific breeds. The age of the calf at weaning time can be specified in the model. NE for production of fat-corrected milk (4% fat), NEl, is 3.09 MJ kg-1 (Moe and Tyrrell, 1975). The gross energy (GE) of fat corrected milk is 2.64 MJ kg-1 (Restle *et al.*, 2003), which implies that conversion efficiency of NEl into milk GE is 85%. Therefore, the heat production from milk production is assumed to be 15% of the NEl. This conversion efficiency is assumed to be independent from the milk production level, lactation stage, and breed (Moe and Tyrrell, 1975). Approximately 90% of the GE in milk is available for calves as NE (Guilloteau *et al.*, 1986). Cows are assumed to convert protein into milk protein at an efficiency of 68% (CSIRO, 2007). This implies that the total protein requirements for lactation can be calculated from the percentage of protein in the milk and the amount of milk produced.

*Heat production under cold stress*

As already explained in the section on the thermoregulation sub-model (section 1.1), an animal increases heat production if heat production from metabolic processes is below the minimum heat release. Animal thus spends additional energy below the TNZ to prevent hypothermia. This additional energy required is calculated as ME, and not as NE, because the heat increment of feeding also results in heat that is used to maintain body temperature.

*Growth*

Under potential production, NE and protein available for growth are, by definition, not restricted by feed-limitation. The diet consisting of 65% wheat and 35% hay, fed *ad libitum*, is assumed to sustain potential production (Van der Linden *et al.*, 2015). The defining factor for potential growth is either the genotype, or the climate via heat or cold stress (Fig. S3). Potential growth might be achieved with other diets than the diet consisting of 65% wheat and 35% hay if the NE and protein requirements are fully supplied by such a diet. If such diets have a lower NE and/or protein content than the ‘potential’ diet, the growth rate is the same, but the feed efficiency is lower. Investigating which diets allow potential growth for specific animals at specific days is complicated and time-consuming. For simplicity, we assume that the *ad libitum* 65% wheat and 35% hay diet prevents NE and protein deficiencies, and sustains potential growth and production of animals.

Still, the NE or protein requirements for growth are not always met before weaning when the 65% wheat and 35% hay diet is fed *ad libitum*. Model simulations show that other diets containing either more NE or CP per kg DM did not eliminate the NE and protein deficiencies before weaning either. For the sake of simplicity, production before weaning is regarded, therefore, as potential production, despite minor limitations (Van der Linden *et al.*, 2018a).

Yes

No

Yes

No

Cold stress?

*Ad libitum* diet consisting of 65% wheat and 35% hay?

Yes

No

Genotype

Cold stress

No

Yes

Maximum digestion capacity reached?

No

Yes

Heat stress?

No

Heat stress

Yes

Feed quantity limitation (NE deficiency)

NE and protein requirements met?

Feed quality limitation / digestion capacity limitation, related to the amount of fill units

Yes

NE more limiting for growth than protein?

No

Feed quantity limitation (protein deficiency)

Heat stress?

Feed quality limitation, related to the heat increment of feeding

*Figure S3.* Decision tree to identify the factors that define and limit growth in LiGAPS-Beef. For explanation, see text. NE = net energy. Green boxes indicate potential growth; orange boxes feed quality limited growth; and the red boxes indicates growth limited by the available feed quantity.

Growth is feed-limited if NE or protein supply from feed intake is lower than the requirements of an animal, and if the diet does not consist of 65% wheat and 35% hay (Fig. S3). The NE and protein for growth are the balancing variables under feed-limited growth and production. LiGAPS-Beef sums the NE and protein requirements for maintenance, physical activity, gestation, and lactation, and the remainder is allocated to growth. NE and protein are not available for growth if the sum of NE or protein requirements for maintenance, physical activity, gestation, and lactation is higher than the total NE and protein supply from feed. Animals have a negative growth rate under this condition, and body tissues are dissimilated to supply the required NE and protein for the metabolic processes (excluding growth).

Feed quality limited growth occurs if the maximum feed intake capacity is reached (Fig. S3). If an animal is at its maximum digestion capacity under cold stress, less NE and protein will be available for growth compared to a situation without cold stress, and hence growth will be reduced. In this particular situation, both the defining factor climate and the limiting factor feed quality influence growth. If crop growth is influenced by both defining and limiting factors, this production situation is named limited production, because limited production also includes defining factors (Van Ittersum and Rabbinge, 1997). If feed quality limitation and cold stress occur simultaneously, feed quality limitation is seen as a primary cause, and cold stress as a secondary one. Feed quality limitation can increase the incidence of heat stress via the heat increment of feeding. The heat increment of feeding is likely to be lower for a diet consisting of 65% wheat and 35% hay than for most other diets containing enough physically effective NDF to sustain rumen health. Heat increment of feeding is a quality characteristic of feed that determines whether or not animals experience heat stress. Feed quality limitation in general, and heat increment of feeding in particular, are seen as a primary cause for not meeting the NE and protein requirements, and heat stress as a secondary cause (Fig. S3).

Feed quantity limitation occurs if NE or protein requirements for growth are not fulfilled, if the ‘potential’ diet is not fed, and if maximum feed capacity is not reached (Fig. S3). In addition, feed quantity limitation cannot coincide with heat stress. Heat stress reduces feed intake, and if animals with low feed availability reduce intake, feed is left and consequently the feed quantity available is not a limiting factor any more. Feed quantity limitation can coincide with cold stress. Feed quantity limitation is seen as a primary cause in this situation, and cold stress as a secondary one. If the available feed quantity is limiting, growth of an animal is determined by either NE or CP supply, depending on which of the two is more limiting for growth (Fig. S3).

Growth is affected by the breed and sex of the animal, and whether the animal has experienced growth retardation. The weight of an animal is equal to the genetic potential weight if an animal did not experience growth retardation before, or completely recovered from it. The genetic potential weight is described by a breed and sex-specific Gompertz curve. The weight of an animal is lower than the genetic potential weight if an animal experienced heat stress or feed-limitation and did not fully recover from this. In LiGAPS-Beef, an animal increases its growth after growth retardation (*i.e.* compensatory growth) if its weight is not equal to the genetic potential weight, and if sufficient NE and protein are available for growth.

In the following paragraphs, we highlight some of the main equations used in the energy and protein utilisation sub-model used to simulate cattle growth. The genetic potential total body weight (TBW) at t days after birth is determined by the breed and sex of the animal, and can be described by a Gompertz curve (Hirooka, 2010) (Eq. 31).

[S2, 9-12, 20]

Where BBW is body weight at birth, MTBW is mature total body weight, RF is a reduction factor, COI is the constant of integration, RM is the rate of maturity, and t is time in days after birth. The reduction factor is added to the equation to allow that the TBW at birth is equal to the birth weight.

The NE and CP requirements for growth are based on the weight increase of body tissues and the NE and CP content of those tissues. The TBW of beef cattle consists of carcass and non-carcass tissue. The carcass tissue is assumed to be 50% of the BBW at birth, irrespective of sex and breed. The maximum carcass fraction in the TBW is assumed to increase linearly with TBW. This carcass fraction in the TBW enables to calculate the carcass weight, CW (Eq. 32).

[S2, 9,18,20]

Where Cfrmax is the maximum carcass fraction at maturity. The carcass consists of the following tissues: bones, muscles, intramuscular fat, intermuscular fat, and subcutaneous fat. Intermuscular fat and subcutaneous fat are combined in the energy and protein utilisation sub-model. The fraction of bones in the carcass is assumed to decrease with increasing carcass weight (Berg and Butterfield, 1968). This fraction is used to calculate bone weight in the carcass, BoW (Eq. 33). The maximum fraction of bones in the carcass is assumed to be 0.25 for young animals.

[S6, 33,34,64]

The muscle fraction in the carcass is calculated via the muscle to bone ratio, M:B using an empirical equation (Eq. 34). The maximum muscle to bone ratio, M:Bmax, is sex and breed specific.

[S2, 19; S6, 68,69]

The muscle weight in the carcass, MuW, is a multiplication of the bone weight and the muscle to bone ratio (Eq. 35). (Berg and Butterfield, 1976)

According to Berg and Butterfield (1976), the weight of intramuscular fat in the carcass, ImfW, increases with an increase in the sum of bone and muscle weight (Eq. 36).

[S6, 56-58]

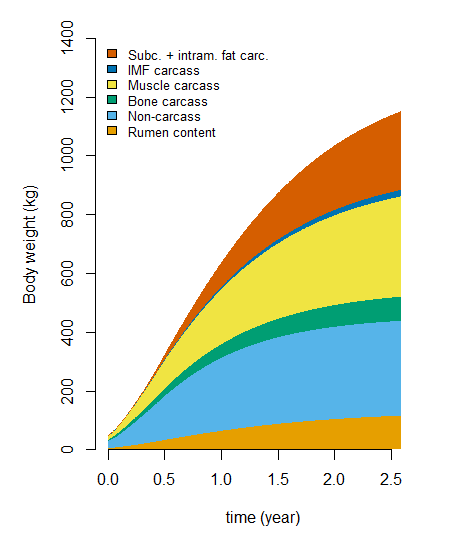
The rest of the carcass weight consists of intermuscular- and subcutaneous fat, FatW (Eq. 37), which is a balancing variable.

Beef is defined as the deboned carcass, which includes MuW, ImfW and FatW (Eq. 38). It should be noted that not all parts from the deboned carcass are edible, or considered edible. The amount of beef produced is used to calculated the feed efficiency of animals and herds.

Weight of the non-carcass tissues is calculated excluding rumen contents, which vary between 10 and 17% of the TBW (Van Soest, 1994). The rumen content was assumed to be equal to 10% of the TBW for beef cattle in LiGAPS-Beef. This enables to calculate the weight of non-carcass tissues, NCW (Eq. 39). The non-carcass tissues consist of different components (*e.g.* organs, head, skin), but these are not distinguished individually in the non-carcass tissue.

[S6, 52]

The Gompertz curve describing TBW (Eq. 31) and the equations describing the weights of body tissues (Eqs 32-39) allow to calculate TBW and tissue weights over time (Fig. S4).



Subc. and interm. fat in carcass

Intramuscular fat in carcass

Muscle tissue in carcass

Bone tissue in carcass

Non-carcass tissues

Rumen content

*Figure S4.* Example of the total body weight and weights of body tissues of a Charolais bull, growing according to its genetic potential. Birth weight was set at 48 kg. Subc. = subcutaneous fat; interm. = intermuscular fat.

Body tissues are each split up in four major components: protein, lipid, ash, and water. Only accretion of protein and lipid is assumed to require NE. Hence, the accretion of ash and water is assumed to occur without any NE requirements. The energy and protein accreted in body tissues is calculated from the fractions of protein and lipid in these tissues.

Variation in protein concentrations in the bone tissue over time is assumed to be small, and therefore neglected. The fraction protein in the bone is 0.230 (Field *et al.*, 1974). The lipid fraction in the bone tissue, LFBONE, is assumed to be dependent on bone weight (Eq. 40). Eq. 40 is an empirical equation fitted to data of Field *et al.* (1974), who reported that the lipid fraction is 0.075 at birth, and increases up to 0.178 at maturity (Fig. S5).

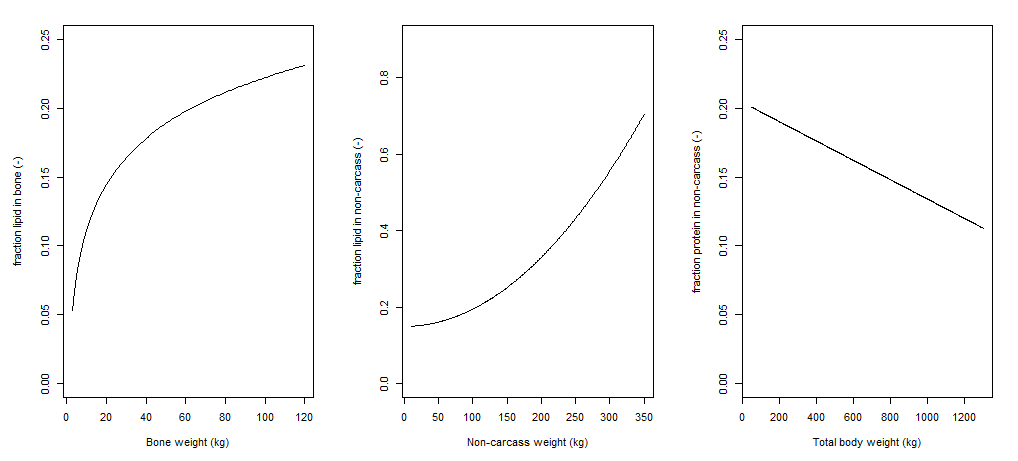
[S2, 16]

The fractions of protein in the muscle tissue are assumed to be fixed at 0.210 (Cosuleanu *et al.*) and the fraction of lipid is assumed to be 0.005 (Warren *et al.*, 2008). The intramuscular, intermuscular, and subcutaneous fat tissues each have a fixed protein fraction of 0.080 and a lipid fraction of 0.700 (Thonney, 2014). The lipid fraction in the non-carcass tissue, LFNONC, increases with the weight of the non-carcass tissue (Eq. 41). The LFNONC is assumed to have a minimum lipid fraction of 0.15 and a maximum of 0.80 (Fig. S5).

Where LIPNONCmin is the minimum lipid content, NCWmax is the maximum non-carcass weight, and LIPNONCmax is the maximum lipid content. A maximum lipid fraction of 0.80 seems high for the non-carcass tissue, especially compared to a lipid fraction of about 0.70 for fat tissue (Thonney, 2014). This high lipid content, however, also accounts for the increase in lipid content of the non-carcass tissue that has been accreted previously.

The protein fraction in the non-carcass tissue decreases linearly with increasing age and TBW, according to Berg (1976). It is assumed that a similar decrease is valid in the non-carcass tissue. Eq. 42 is fitted from data presented by Berg and Butterfield (1976) (Fig. S4).

[S6, 80,81]



*Figure S5.* Fraction of lipid in bone (Eq. 40, left) and in the non-carcass tissue (Eq. 41, middle), and the fraction of protein in the non-carcass tissue (Eq. 42, right). The data in the curves represent a Charolais bull.

The GE content, or combustion value, is 23.8 kJ g-1 for protein and for 39.6 kJ g-1 for fat (Emmans, 1994). The efficiency for protein accretion is assumed to be 0.54 and 0.74 for fat accretion (Trottier, 2016). Hence the NE required for growth is 44.0 kJ g-1 for protein and 53.5 kJ g-1 for fat. The NE that does not end up as retained energy in body tissue is converted into heat (46% for protein, 26% for lipid accretion).

The derivative of tissue weight over time is the tissue growth rate. The total energy requirements for growth of a body tissue can be calculated as the NE required for protein and fat accretion in the tissue per unit of time. Total NE for growth, NEgr, is the sum of the NE for growth of all five body tissues (Eq. 43). Since the rumen contents do not belong to the body tissues, the increase in rumen content and subsequently TBW does not require NE.

[S6, 46-49, 51]

Total NE accreted in the body is obtained by replacing the NE requirement for protein and fat (44.0 and 53.5 kJ g-1) by the energy requirements for accretion (23.8 and 39.6 kJ g-1) in Eq. 43. Protein requirements for growth are the proteins that are accreted in body tissue, plus the protein requirements to synthesize protein and lipid.

Like for maintenance and physical activity, it is assumed that NE and protein requirements are coupled. The amount of retained protein in tissues is the sum of protein accreted in each of the five body tissues. The amount of protein required for protein accretion in tissues is the sum of protein accreted in each of the five body tissues. The NE that is converted into heat during lipid and protein accretion is assumed to be associated with a proportional demand for protein. Protein requirement for lipid and protein accretion is assumed to require 0.478 g CP MJ-1 heat released during lipid and protein accretion. The information above allows to calculate the TBW, weights of tissues, and the corresponding NE and protein requirements for growth.

So far, the explanation on growth is based on the assumption that an animal is able to grow according to its genetic potential, without any defining or limiting factors other than the genotype. The next section deals with an animal that shows compensatory growth after experiencing growth retardation in the past.

*Compensatory growth*

Compensatory growth is an accelerated growth after a period of growth retardation to reach the weight the animal would have had if growth retardation would not have occurred (Hornick *et al.*, 2000). Compensatory growth is observed in beef cattle after periods characterised by feed limitation (Horton and Holmes, 1978, Carstens *et al.*, 1991). The magnitude of compensatory growth for each tissue is assumed to be a function of the difference between tissue weight and the genetic potential weight of this tissue (Fig. S4). Accelerated growth is assumed to be at least 0% and at most 20% (guesstimate) higher than the genetically potential growth (Eq. 44).

Where Comp is the multiplicative of the genetically potential growth, TW is tissue weight, and TWpot. is the genetic potential weight of a tissue. Compensatory growth of a tissue does not occur if tissue weight equals the genetically potential weight of the tissue (Eq. 44). Eq. 44 mainly allows to calculate potential growth in growing animals. This would imply that adult animals would hardly be able to recover from growth retardation or weight loss, since their genetic potential growth at later age is low. It is assumed, therefore, that compensatory growth is realised too if adult animals experience weight loss or have experienced growth retardation (Eq. 45).

[S6, 44]

Where NEcomp gr is the NE for compensatory growth, COMPFACT is a factor determining compensatory growth, and NEgr max is the maximum NE for growth an animal has ever had. The maximum NE for growth corresponds to the inflection point in the Gompertz curve. The factor determining compensatory growth (COMPFACT) is set at a value of four. The total NE under compensatory growth is the result of the multiplicative of the genetic potential growth (Eq. 44) and NE for compensatory growth (Eq. 45). If abundant NE and CP are available, compensatory growth of all tissues is proportional to the tissue weight according to the Gompertz curve divided by the tissue weight with growth retardation. So far, NE and CP supply were equal to NE and CP requirements. The next section deals with conditions were either NE or CP supply, or a combination of both, is below the requirements.

*Reduced growth*

LiGAPS-Beef sums the total NE and protein requirements for maintenance, physical activity, gestation, lactation, and additional heat production below the TNZ (*i.e.* under cold stress). The NE and protein for growth are balancing variables in the model. Reduced growth occurs if the NE and/or protein requirements for growth are not fully met. A reduced growth does not affect all tissues to the same extent. The growth of the subcutaneous and intermuscular fat tissues decreases most in periods with reduced growth, whereas the non-carcass tissue and the bone tissue in the carcass are affected least. Under negative growth (see next section), the subcutaneous and intermuscular fat tissues are dissimilated to supply energy. To prevent that the weight of the subcutaneous and intermuscular tissue weight to become negative or unrealistically low, some NE is allocated to the subcutaneous and intermuscular tissue, NESI, under reduced growth (Eq. 46).

[S6, 36,45]

Where SI is the weight of the subcutaneous and intermuscular fat tissue, and SIpot. is the genetic potential weight of the subcutaneous and intermuscular fat tissue according to the Gompertz curve, and EBW0.75 is the metabolic body weight. After NESI is deducted for the amount of NE under NE deficiency, the remaining NE is allocated over all tissues in the same way as under compensatory growth. Unlike NE deficiency, protein deficiency is assumed to affect all body tissues to the same extent.

*Negative growth*

If the NE from feed intake is lower than the NE requirements for maintenance, physical activity, gestation, and milk production, NE requirements for growth are zero for all tissues. The animal also has to dissimulate its body tissue to provide additional NE and protein (Beatty *et al.*, 2004). The NE required to sustain the metabolic processes (excluding growth) is obtained from the subcutaneous and intermuscular fat tissue (60%), muscle tissue (10%), and non-carcass tissue (30%) to balance the NE requirements and supply. Given the GE content of lipid (39.6 kJ g-1) and protein (23.4 kJ g-1) (Emmans, 1994), and the proportions of lipid (70%) and protein in fat tissue (8%) (Thonney, 2014), the total GE content of fat tissue is 29.6 MJ kg-1. The GE content of muscle tissue is 5.2 MJ kg-1, and the GE content of non-carcass tissue, GEnc, is variable, as its protein and lipid content is variable. The GE from body tissues is assumed to be converted to NE with an efficiency of 90%. If NE is deficient, the difference between NE requirement and supply from feed, NEdef, determines the decrease in body weight, DBW (Eq. 47).

[S6, 41]

*Heat generation from metabolic processes*

The NE for maintenance, NE for physical activity, and the heat increment of feeding are fully converted into heat. Heat production is an output of the energy and protein utilisation sub-model and an input for the thermoregulation sub-model. The efficiency of energy accretion in body tissues is 54% for protein and 74% for fat (Trottier, 2016). This implies that 46% of NE for protein accretion and 26% of NE for fat accretion are converted into heat.

The efficiency of NE into body tissue of the developing foetus during gestation is assumed to be approximately 14% in ruminants, excluding the weight of concepta (Weiss, Rattray *et al.*, 1974, Jarrige, 1989). The weight of the concepta equal 67% of weight of the foetus, FBW (Jarrige, 1989). Hence, the efficiency of NE for gestation is assumed to be 23.4%, and heat production from gestation is 76.6% from the NE allocated to gestation. In addition, 85% of the NE for lactation, NEl, is assumed to end up as GE in milk (*i.e.* retained in milk fat, milk protein, and lactose). Total heat production, H­t, can be calculated, therefore, from the total ME requirements and the GE retained in body tissues and milk (Eq. 48).

[S6, 74]

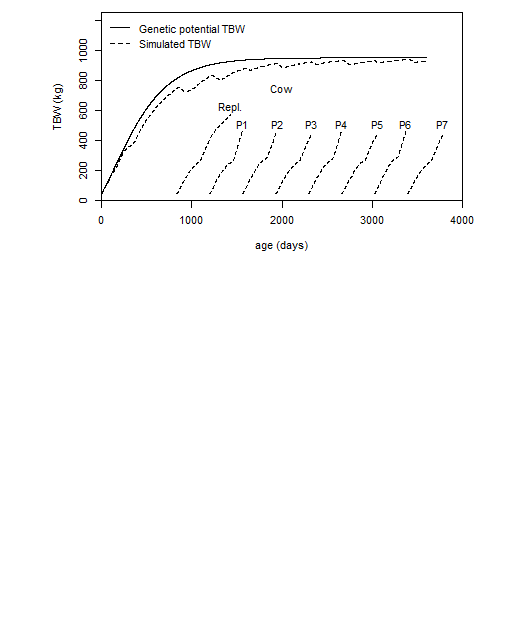
Where MEt is the total ME from metabolic processes, NEaccr pr is the NE for growth accreted as protein, NEaccr li is the NE for growth accreted as lipid, NEges is the NE for gestation, and NEl is the NE for lactation.

## 1.5 Upscaling to herd level

The aim of LiGAPS-Beef is to assess potential and feed-limited growth and production of beef cattle, and to identify the factors that define and limit growth (Fig. S3). The model is written against the background of the sustainable intensification of agricultural production. Sustainable intensification is defined as increasing the agricultural production per unit of land while minimizing the negative impact on the environment (Garnett and Godfray, 2012, Garnett *et al.*, 2013). The amount of beef produced per unit of land is the multiplicative of feed production (t DM ha-1 year-1) and feed efficiency of cattle herds (kg beef t-1 DM feed). Cattle herds consist of multiple animals differing in age and sex. Assessing the potential or limited beef production per unit of land thus requires to account for herd dynamics. The three sub-models of LiGAPS-Beef allow to simulate an individual animal. This section contains, therefore, a description on the upscaling from the individual animal level to the herd level.

The upscaling from animal to herd level is largely based on information presented in Van der Linden *et al.* (2015). Herds are split up in a productive herd (*i.e.* calves raised for beef production) and a reproductive herd, consisting of cows and replacement heifers. Maintaining the herd size implies that the number of cows slaughtered must equal the number of replacement heifers entering the reproductive herd. The smallest possible herd consists of one reproductive cow, which produces offspring. The smallest possible herd is referred to as a herd unit. As the ratio between cows and bulls is generally high, reproductive bulls are neglected in a herd unit. The reproductive cow in the smallest possible herd can produce several calves, and has to be replaced by a heifer at the end of her lifetime. Since a heifer replaces the reproductive cow, the beef production from a herd unit is derived from the cow and her calves not used for replacement. The heifer used for replacement gives rise to a new herd unit. Herds are assumed to be multiplicatives of a herd unit (Van der Linden *et al.*, 2015).

The reproductive cow is slaughtered after weaning a specific number of calves, or after reaching a maximum age. Both numbers can be set by the model user. The first calf of the cow is assumed to be a female calf that is used as a replacement of the cow. Additional calves born after the first calf are all used for beef production (Fig. S6).



*Figure S6.* Example of a model simulation of total body weight (TBW) in a herd unit over time (dashed lines), plus a replacement calf (Repl.). The Gompertz curve indicating the genetic potential TBW of the reproductive cow is indicated by the solid line. The herd unit starts with the birth of a female calf, which becomes a reproductive cow that gives birth to its first calf after 836 days (2.3 years). This replacement calf is not part of the herd unit, but gives rise to a new herd unit. The TBW of the replacement calf is shown up to the age at first conception. The calves born after the replacement calf are raised for beef production (P1-7), and slaughtered at a weight of 460 kg TBW in this example. The cow is culled after weaning the eighth calf (P7).

Assumptions in LiGAPS-Beef are that birth of twins and triplets is negligible; that the male:female ratio of calves is one; and that the mortality is zero under potential and feed-limited production. The minimum intercalving period is assumed to be one year, and the maximum age at conception was ten years. The culling rate of cows is also taken into account in LiGAPS-Beef. The culling rate is the percentage of cows culled per year. For simplicity, culling of reproductive cows is assumed to start after birth of the first calf, so all cows give birth to at least one calf. The culling rate affects the number of female and male calves in a herd unit. At a culling rate of 50% per year, a maximum age of conception of 10 years, and a minimum calving interval of one year, on average one female calf and one male calf are born in a herd unit. The female calf is used as a replacement heifer and gives rise to a new herd unit (Table S7). The beef production in this herd unit consists of the beef produced by the reproductive cow and the bull (calf). At a lower culling rate of 17%, on average 4.56 calves are born in a herd unit, of which are 2.24 female (49.1%) and 2.32 are male (50.9%) (Table S7). The beef production in such a herd unit consists of the beef produced by the cow, 2.32 bulls, and 1.24 heifers not used for replacement. A decreasing culling rate increases the number of calves per herd unit and the average lifespan of the cow. The order of male and female calves is adjusted in LiGAPS-Beef to approach male:female ratio, which is assumed to be one. Calves used for beef production can be slaughtered at different weights, which can be set by the model user.

***Table S7.*** Numbers of male (M) and female (F) calves in a herd unit with a maximum of eight calves per cow. Culling rates of reproductive cows are 50% and 17% per year after birth of the first calf.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Animal |  |  | Replacement rate1 | |  |  |
|  | 50% | | | 17% | | |
|  | Sex | Probability | Number | Sex | Probability | Number |
| Cow | F | 100% | 1.00 | F | 100% | 1 |
| Replacement calf2 | F | 100% | 1.00 | F | 100% | 1 |
| 2nd calf | M | 50% | 0.50 | M | 83% | 0.83 |
| 3rd calf | M | 25% | 0.25 | M | 69% | 0.69 |
| 4th calf | M | 13% | 0.13 | F | 57% | 0.57 |
| 5th calf | M | 6% | 0.06 | M | 47% | 0.47 |
| 6th calf | M | 3% | 0.03 | F | 39% | 0.39 |
| 7th calf | M | 2% | 0.02 | M | 33% | 0.33 |
| 8th calf | M | 1% | 0.01 | F | 27% | 0.27 |
| Total male calves |  |  | 0.99 |  |  | 2.32 |
| Total females calves3 |  |  | 0.00 |  |  | 1.24 |

1 Replacement rate after birth of the first calf, in % per year for each age cohort.

2 The replacement calf is not part of the herd unit.

3 Excludes the replacement calf, which is not part of the herd unit.

*Upscaling under potential and feed-limited beef production*

Crop management is assumed to be optimal under potential and limited crop production (Van Ittersum and Rabbinge, 1997, Van Ittersum *et al.*, 2013). Likewise, herd management should be optimal too under potential and feed-limited beef production. The culling rate of reproductive cows and the slaughter weight of calves must be adjusted to maximize the feed efficiency (FE, expressed in kg beef t-1 DM feed intake) of a herd unit.

The culling rate of cows is set at 50% per year after birth of the first calf under potential and feed-limited production, which is considered the maximum culling rate. Adopting a culling rate of 50% results in one female calf per herd unit for replacement, and one male calf for beef production (Table S7). Cattle populations will decrease if the culling rate is higher than 50%, because the number of cows slaughtered exceeds the number of female calves born (assuming a male:female ratio of one). The FE is maximized by adjusting the culling rate to 50% per year for two reasons. First, increasing the culling rate results in a lower age at slaughter, and hence a lower average weight of reproductive cattle. A lower average weight reduces the NE and protein requirements for maintenance and physical activity. Second, young cows still grow themselves while producing calves, whereas older cows have often growth rates close to zero.

The maximum age for conception is set at 10 years, under the assumption that ageing does not allow cattle to maintain potential or feed-limited production (Van der Linden *et al.*, 2015), for example due to worn teeth. Although ageing processes may differ between cattle breeds and differ between production levels, the maximum number of calves and age up to which conception can take place are fixed under optimal management. Since only a small percentage of cattle achieves the maximum age of ten years (0.50.7 = 0.008/100 = 0.8%), the choice for the maximum age at slaughter does not affect the maximum FE of a herd unit to a large extent under a culling rate of 50% per year after birth of the first calf.

The slaughter weight of calves under optimal management comprises only the slaughter weight of the male calf per herd unit, as the female calf is used as a replacement for the reproductive cow at a culling rate of 50%. Each herd unit has, on average, one cow and one bull calf (Table S7). The diet of a calf before weaning consists partly of milk, and hence FE is high in this phase. As the lipid content in the body usually increases over age, and more NE is required per kg at increasing body weights, the FE of cattle decreases over time. If the FE of the bull (calf) at a specific moment is higher than the average FE of the reproductive cow during her lifespan, the average FE per herd unit is increased further by keeping the bull calf in the herd. If the FE of the bull at a specific moment is lower than the average FE of the reproductive cow during her lifespan, the FE per herd unit is decreased further by keeping the bull calf in the herd. Hence, the optimum slaughter age for a bull calf is the moment where its FE is equal to the average FE of the reproductive cow. The FE of a herd unit, FEHU, under optimal management is calculated as a weighted average of the FE of the cow and the bull calf, taking into account their beef production levels (Eq. 49).

Where FER is the feed efficiency of the reproductive cow, BeefR is the beef production of the reproductive cow (in kg), FEBC is the feed efficiency of the bull calf, and BeefBC is the beef production of the bull calf (in kg).

## 1.6 Getting started with LiGAPS-Beef

The model LiGAPS-Beef has been written in the programming language ‘R’ (R Core Team, 2013). Version 2.15.3 or a more recent version of R is recommended. The R programming language is freely available, and can be downloaded free of charge. No additional R-packages are required to run the model itself. RStudio, the interface for R, facilitates the use of LiGAPS-Beef (RStudio Team, 2015). Version 0.98 or a more recent version of RStudio is recommended.

The source code of LiGAPS-Beef is freely accessible. We emphasize that the source code is a work in progress, and it may contain errors, defects, and bugs, even after repetitive testing. For this reason, the users of LiGAPS-Beef work on the model on an ‘as is’ basis. No warranties of any kind are given, including its suitability for a specific purpose and absence of errors. We are not liable for any direct or indirect damage of any kind resulting from the use of LiGAPS-Beef. Model users deciding to adapt the code for their own purposes are free to do so, but any change is at their own responsibility. For the full disclaimer coming along with LiGAPS-Beef, see the licence agreement on the model portal of the Plant Production Systems group of Wageningen University, the Netherlands, which is also available as a pdf file (<http://models.pps.wur.nl/content/licence_agreement>).

The source code available consist of the following files:

* A full version of LiGAPS-Beef (file: LiGAPSBeef20180301\_herd.R). This file contains the three integrated sub-models of LiGAPS-Beef, and allows to simulate beef cattle at both the animal and herd level. The source code reproduces the results for case 1, 3, 5, 7, 9 and 10 at herd level, which are listed in Table 1 and 3 of the main paper (Van der Linden *et al.*, 2018a). In addition, the source code reproduces the figures on TBW, feed intake, and the factors that define and limit growth for these cases, which are presented in Chapter 2 of this Supplementary Material. A brief description on the structure of the source code is given in Appendix II, and the list with loops used in the source code is given in Appendix III.
* The thermoregulation sub-model (file: Thermoregulation submodel20170922.R). The source code reproduces Fig. 2 of the accompanying paper on model sensitivity analysis and evaluation of sub-models (Van der Linden *et al.*, 2018b).
* The feed intake and digestion sub-model (file: Feed digestion submodel20170907.R). As feed intake is determined by the thermoregulation sub-model and the energy and protein utilisation model, feed intake was not included in this version of the feed intake and digestion sub-model. The source code reproduces Fig. 4 of the accompanying paper on model sensitivity analysis and evaluation of sub-models (Van der Linden *et al.*, 2018b).
* An R-script to calculate solar radiation per m2 coat and cloud cover expressed in Ω (file: Weatherfilesynthesis20151208.R).

In addition, one input file with daily weater data is provided:

* A input weather file for LiGAPS-Beef (file: FRACHA19982012.csv). This file contains daily weather data for Charolles (46.4°N, 4.3°E), France, from the year 1998 up to 2012. The daily weather data included in this file can be found in Table S1. The weather data are obtained from the Agri4Cast Resources Portal (Agri4Cast, 2013).

The source code can be opened with RStudio. Source code for the thermoregulation sub-model and feed intake and digestion sub-model does not require any input files, nor any editing in the code before the code can be run. Plotting Fig. 2 of the paper on sensitivity analysis and evaluation of sub-model requires the R-package ‘plot3D’.

The full version of LiGAPS-Beef requires an input weather file. The directory and name of this weather file must be specified in line 233 of the code (e.g. "C:/R/FRACHA19982012.csv"). The other weather files listed in line 235 are not required to run LiGAPS-Beef for the cases 1, 3, 5, 7, 9, and 10. LiGAPS-Beef can be run after entering the directory and name of the weather file correctly. Simulations for the cases 1, 3, 5, 7, 9, and 10 may take a few minutes, depending on the computation capacity of the computer used.

The source code of LiGAPS-Beef is accessible, and can be downloaded for free. The development team of LiGAPS-Beef would like to keep an overview of modelling activities with LiGAPS-Beef, and stay informed about modelling activities where LiGAPS-Beef is involved. We kindly request model users, therefore, to inform us about model applications by sending an email to the development team (contact: [aart.vanderlinden@wur.nl](mailto:aart.vanderlinden@wur.nl)). Comments, suggestions, bug reports, and other feedback on LiGAPS-Beef is highly valued, and can be sent to the development team by email.

The source codes listed above are freely accessible. The same source code is accessible on the model portal of the Plant Production Systems group of Wageningen University, the Netherlands (<http://models.pps.wur.nl/content/ligaps-beef>). Updated versions of LiGAPS-Beef will appear on this model portal, as well as source code with new applications of LiGAPS-Beef.

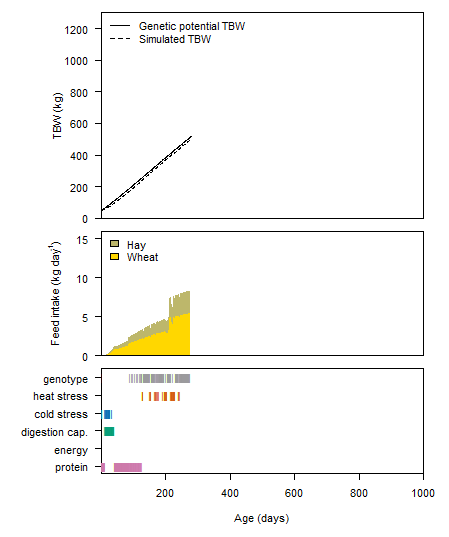
2. Model illustration

Ten cases are selected in the main paper (Tables 1-3) to illustrate model behaviour with different cattle breeds, climates, and feeding strategies, both at animal level and herd level. In this section of the Supplementary Material, results are given for each of these simulations. The information presented below is additional information to the main paper (Tables 2 and 3; Fig. 4).

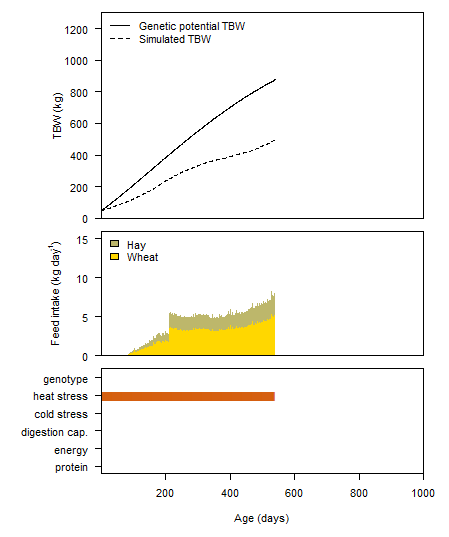
The figures in this section each consist of sub-graphs with information on TBW dynamics, feed intake, and an indication of the factors that define and limit growth over time. The graph with the TBW dynamics shows the Gompertz curve of the animal (Eq. 31), which is indicated by the solid black line. The simulated TBW is indicated by a dashed line. The graph with the factors that define and limit growth indicates whether and when the genotype, heat stress, cold stress, digestion capacity limitation, energy deficiency, and protein deficiency are defining or limiting growth. The graph presenting the defining and limiting factors indicates the six aforementioned biophysical factors by vertical bars. When a biophysical factor is abundant in a specific period, the individual vertical bars form a horizontal bar. Because the width of the individual vertical bars is larger than the width of one day on the x-axis, appearance of joint horizontal bars does not imply that stress occurred during the whole period.

2.1 Model illustration at the animal level

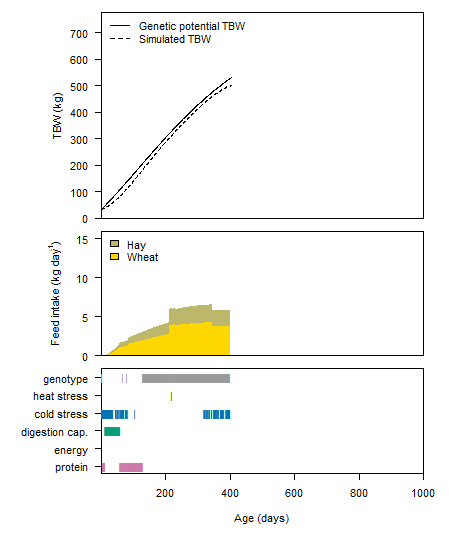
The graphs in this section provide additional information on the simulation results for individual animals. Ten scenarios are described in Table 1 of the main paper, and their results are presented in Table 2. The abbreviations for the cases correspond to the abbreviations used in Tables 1 of the main paper. Hay used in diets is good quality hay. The birth date of the animals is the 1st of January.



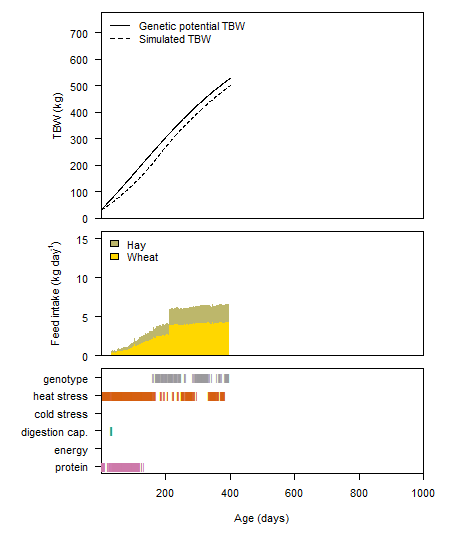
*Figure S7.* Total body weight (TBW), feed intake, and the factors that define and limit growth of Charolais bulls in France. Results correspond to case 1, Pot Ch Fr. Bulls are housed in stables from December to March, and are grazing from April to November. The diet consists of 65% wheat and 35% hay, which allows potential growth. Slaughter weight = 500 kg TBW; Slaughter age = 278 days; Beef production = 230 kg; Feed intake = 1063 kg DM; FE = 216 g beef kg-1 DM feed.



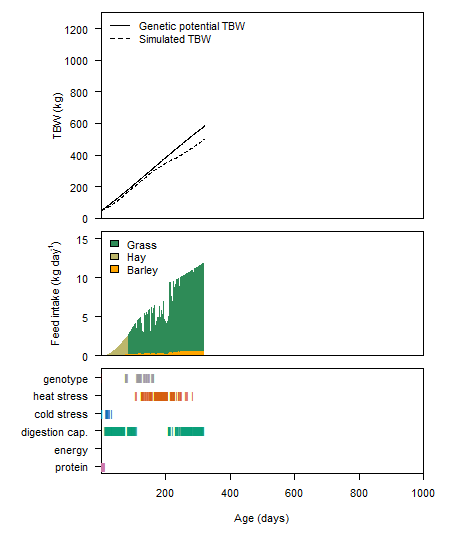
*Figure S8.* Total body weight (TBW), feed intake, and the factors that define and limit growth of Charolais bulls in Australia. Results correspond to case 2, Pot Ch Au. Bulls are grazing year-round. The diet consists of 65% wheat and 35% hay, which allows potential growth. Slaughter weight = 500 kg TBW; Slaughter age = 540 days; Beef production = 213 kg; Feed intake = 2059 kg DM; FE = 104 g beef kg-1 DM feed.



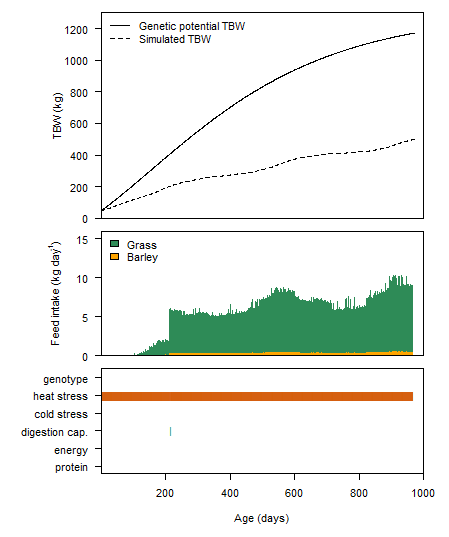
*Figure S9.* Total body weight (TBW), feed intake, and the factors that define and limit growth of ¾ Brahman × ¼ Shorthorn bulls in France. Results correspond to case 3, Pot B×S Fr. Bulls are housed in stables from December to March, and are grazing from April to November. The diet consists of 65% wheat and 35% hay, which allows potential growth. Slaughter weight = 500 kg TBW; Slaughter age = 402 days; Beef production = 243 kg; Feed intake = 1667 kg DM; FE = 146 g beef kg-1 DM feed.



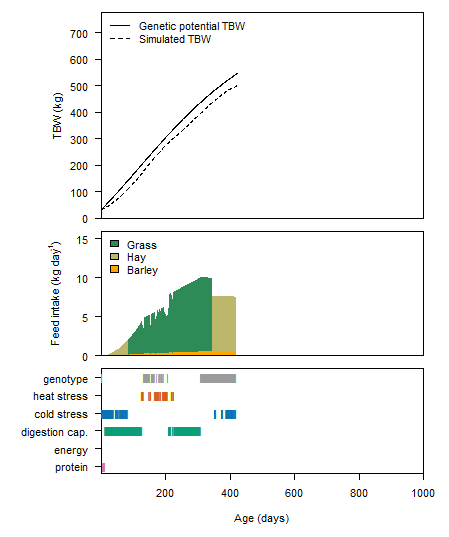
*Figure S10.* Total body weight (TBW), feed intake, and the factors that define and limit growth of ¾ Brahman × ¼ Shorthorn bulls in Australia. Results correspond to case 4, Pot B×S Au Bulls are grazing year-round. The diet consists of 65% wheat and 35% hay, which allows potential growth. Slaughter weight = 500 kg TBW; Slaughter age = 400 days; Beef production = 240 kg; Feed intake = 1602 kg DM; FE = 150 g beef kg-1 DM feed.



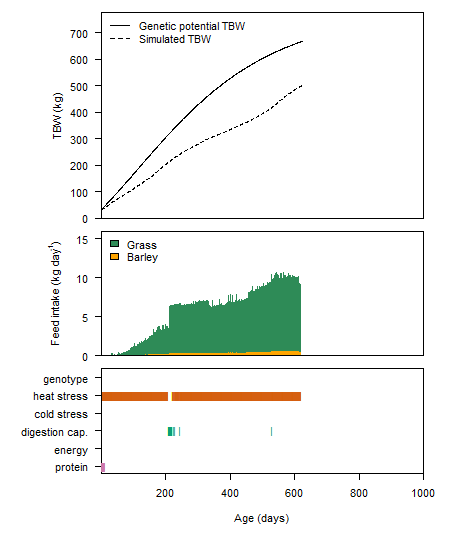
*Figure S11.* Total body weight (TBW), feed intake, and the factors that define and limit growth of Charolais bulls in France. Results correspond to case 5, FQlty Ch Fr. Bulls are housed in stables from December to March, and are grazing from April to November. The diet consists of 5% barley and 95% hay (December-March) and 5% barley and 95% grass (April-November). Slaughter weight = 500 kg TBW; Slaughter age = 321 days; Beef production = 220 kg; Feed intake = 1802 kg DM; FE = 122 g beef kg-1 DM feed.



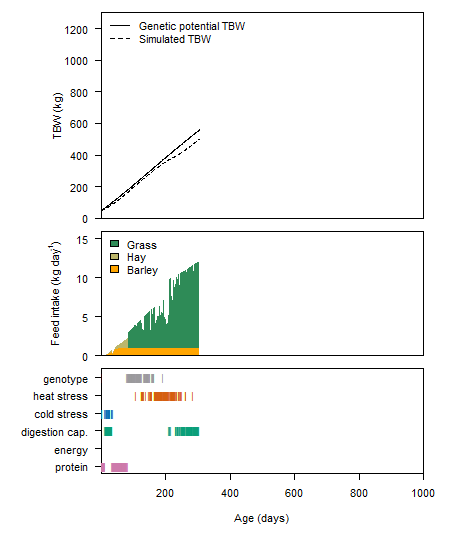
*Figure S12.* Total body weight (TBW), feed intake, and the factors that define and limit growth of Charolais bulls in Australia. Results correspond to case 6, FQlty Ch Au. Bulls are grazing year-round. The diet consists of 5% barley and 95% grass. Slaughter weight = 500 kg TBW; Slaughter age = 970 days; Beef production = 237 kg; Feed intake = 5408 kg DM; FE = 44 g beef kg-1 DM feed.



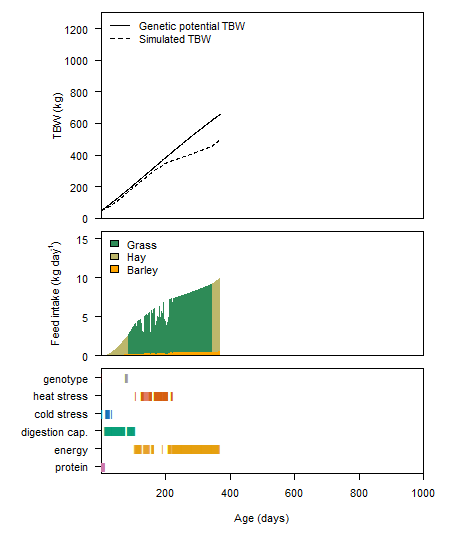
*Figure S13.* Total body weight (TBW), feed intake, and the factors that define and limit growth of ¾ Brahman × ¼ Shorthorn bulls in France. Results correspond to case 7, FQlty B×S Fr. Bulls are housed in stables from December to March, and are grazing from April to November. The diet consists of 5% barley and 95% hay (December-March) and 5% barley and 95% grass (April-November). Slaughter weight = 500 kg TBW; Slaughter age = 421 days; Beef production = 240 kg; Feed intake = 2431 kg DM; FE = 99 g beef kg-1 DM feed.



*Figure S14.* Total body weight (TBW), feed intake, and the factors that define and limit growth of ¾ Brahman × ¼ Shorthorn bulls in Australia. Results correspond to case 8, FQlty B×S Au. Bulls are grazing year-round. The diet consists of 5% barley and 95% grass. Slaughter weight = 500 kg TBW; Slaughter age = 622 days; Beef production = 244 kg; Feed intake = 3578 kg DM; FE = 68 g beef kg-1 DM feed.



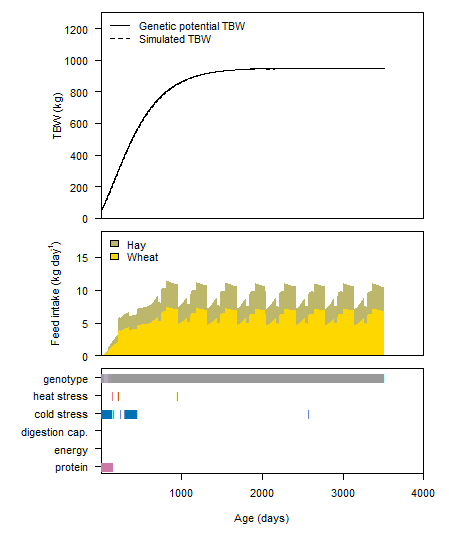
*Figure S15.* Total body weight (TBW), feed intake, and the factors that define and limit growth of Charolais bulls in France. Results correspond to the case 9, FQlty Ch Fr 1 kg. Bulls are housed in stables from December to March, and are grazing from April to November. The diet consists of barley, hay (December-March), and grass (April-November). Barley is maximum 65% of the diet, or maximum 1 kg DM day-1. The remaining part of the diet is hay or grass. Slaughter weight = 500 kg TBW; Slaughter age = 305 days; Beef production = 221 kg; Feed intake = 1648 kg DM; FE = 134 g beef kg-1 DM feed.



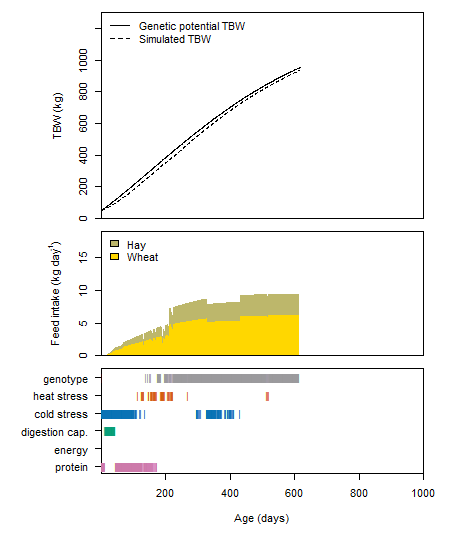
*Figure S16.* Total body weight (TBW), feed intake, and the factors that define and limit growth of Charolais bulls in France. Results correspond to case 10, FQlty Ch Fr 2%. Bulls are housed in stables from December to March, and are grazing from April to November. The diet consists of 5% barley and 95% hay (December-March), or 5% barley and 95% grass (April-November). Feed availability is 2% of the TBW. Slaughter weight = 500 kg TBW; Slaughter age = 370 days; Beef production = 219 kg; Feed intake = 1979 kg DM; FE = 111 g beef kg-1 DM feed.

2.2 Model illustration at the herd level

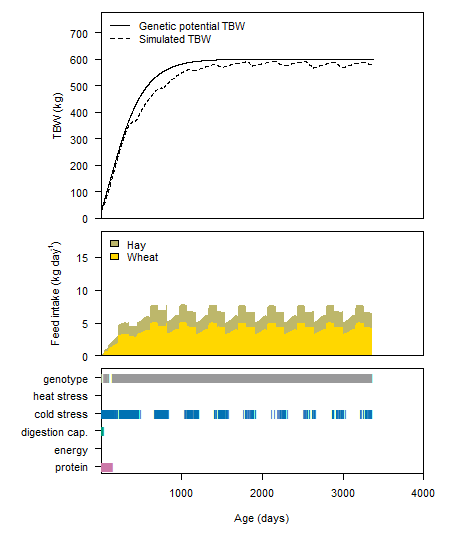
The graphs in this section provide additional information on the simulation results at the herd level. Ten cases are described in Table 1 of the main paper, and their results are presented in Table 3. The abbreviations given below for the scenarios correspond to the abbreviations used in Table 1 of the main paper. The birth date of the reproductive cow in a herd unit is the 1st of January. Hay used in diets is good quality hay. A herd unit consists of one reproductive cow and one bull calf (Van der Linden *et al.*, 2015, Van der Linden *et al.*, 2018a). The cow and bull calf are presented in different graphs (indicated by an ‘a’ for the reproductive cow and a ‘b’ for the calf). A more elaborate description of a herd unit under potential and feed-limited production can be found in Van der Linden *et al.* (2015), the main paper (Van der Linden *et al.*, 2018a), and section 1.4 of this Supplementary Material. Although a small fraction of the cows has a probability of giving birth to eight calves (Table S7), the full life span of the animals is plotted in the graphs below. Beef production and FE in the subscripts of the graphs are, however, presented for an average cow.



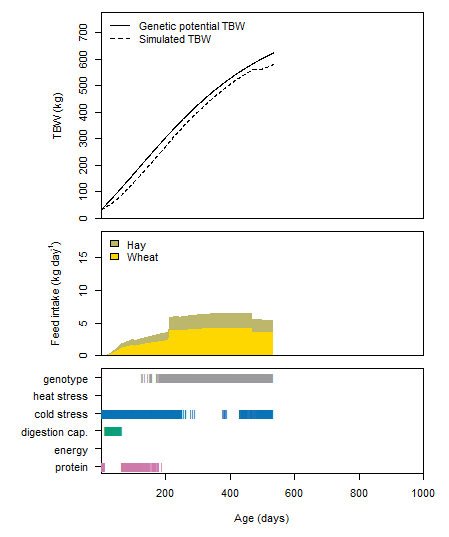
*Figure S17a.* Total body weight (TBW), feed intake, and constraining factors of reproductive Charolais cows in France. Results correspond to case 1, Pot Ch Fr. Cows are housed in stables from December to March, and are grazing from April to November. The diet consists of 65% wheat and 35% hay, which allows potential growth. Beef production = 508 kg; FE = 52 g beef kg-1 DM feed.



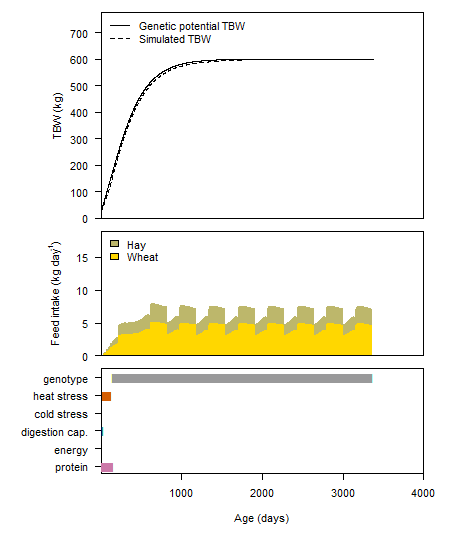
*Figure S17b.* Total body weight (TBW), feed intake, and constraining factors of a bull calf in France. Results correspond to case 1, Pot Ch Fr. Calves are housed in stables from December to March, and are grazing from April to November. The diet consists of 65% wheat and 35% hay, which allows potential growth. Slaughter weight = 936 kg TBW; Beef production = 490 kg; FE = 124 g beef kg-1 DM feed.



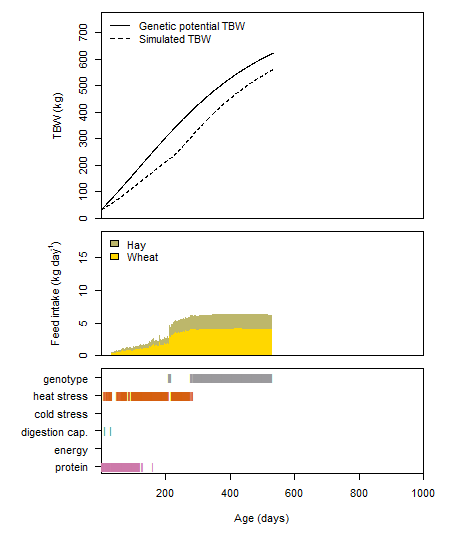
*Figure S18a.* Total body weight (TBW), feed intake, and the factors that define and limit growth of ¾ Brahman × ¼ Shorthorn reproductive cows in France. Results correspond to case 3, Pot B×S Fr. Cows are housed in stables from December to March, and are grazing from April to November. The diet consists of 65% wheat and 35% hay, which allows potential growth. Beef production = 271 kg; FE = 44 g beef kg-1 DM feed.



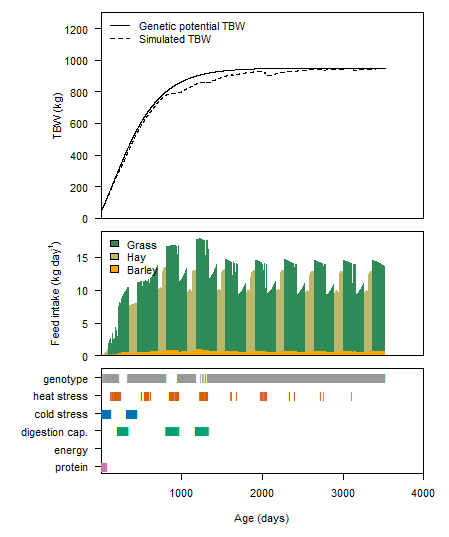
*Figure S18b.* Total body weight (TBW), feed intake, and the factors that define and limit growth of a ¾ Brahman × ¼ Shorthorn bull calf in France. Results correspond to case 3, Pot B×S Fr. Calves are housed in stables from December to March, and are grazing from April to November. The diet consists of 65% wheat and 35% hay, which allows potential growth. Slaughter weight = 580 kg TBW; Beef production = 292 kg; FE = 125 g beef kg-1 DM feed.



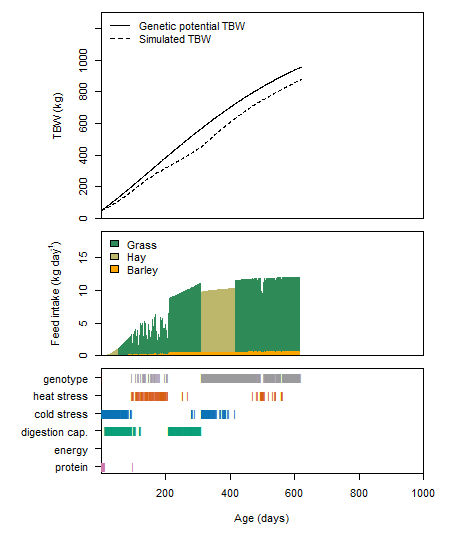
*Figure S19a.* Total body weight (TBW), feed intake, and the factors that define and limit growth of ¾ Brahman × ¼ Shorthorn reproductive cows in Australia. Results correspond to case 4, Pot B×S Au. Cows are grazing year-round. The diet consists of 65% wheat and 35% hay, which allows potential growth. Beef production = 298 kg; FE = 46 g beef kg-1 DM feed.



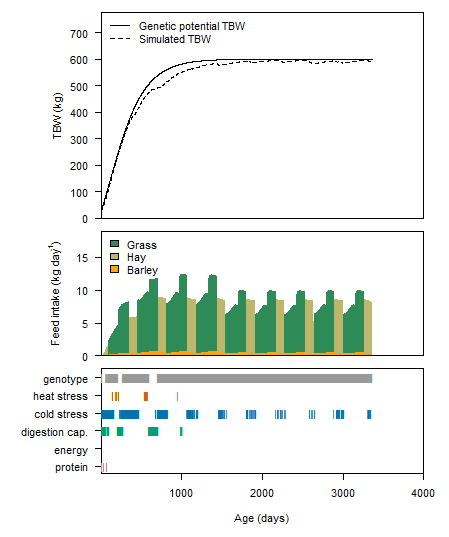
*Figure S19b.* Total body weight (TBW), feed intake, and the factors that define and limit growth of a ¾ Brahman × ¼ Shorthorn bull calf in Australia. Results correspond to case 4, Pot B×S Au. Calves are grazing year-round. The diet consists of 65% wheat and 35% hay, which allows potential growth. Slaughter weight = 560 kg TBW; Beef production = 275 kg; FE = 124 g beef kg-1 DM feed.



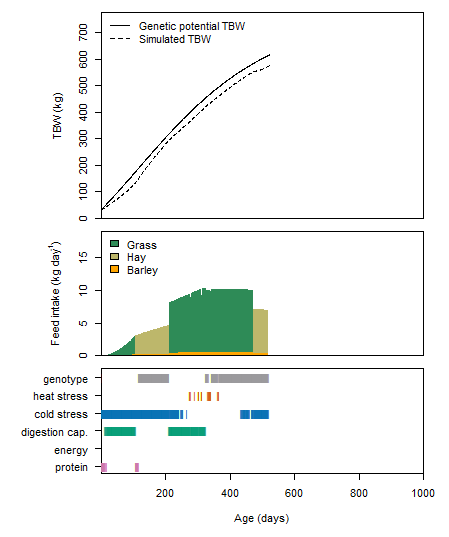
*Figure S20a.* Total body weight (TBW), feed intake, and the factors that define and limit growth of reproductive Charolais cows in France. Results correspond to case 5, FQlty Ch Fr. Cows are housed in stables from December to March, and are grazing from April to November. The diet consists of 5% barley and 95% hay (December-March) and 5% barley and 95% grass (April-November). Beef production = 467 kg; FE = 33 g beef kg-1 DM feed.



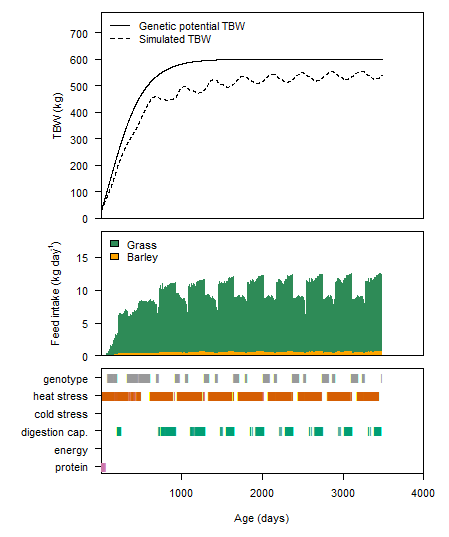
*Figure S20b.* Total body weight (TBW), feed intake, and the factors that define and limit growth of a Charolais bull calf in France. Results correspond to case 5, FQlty Ch Fr. Calves are housed in stables from December to March, and are grazing from April to November. The diet consists of 5% barley and 95% hay (December-March) and 5% barley and 95% grass (April-November). Slaughter weight = 878 kg TBW; Beef production = 444 kg; FE = 103 g beef kg-1 DM feed.



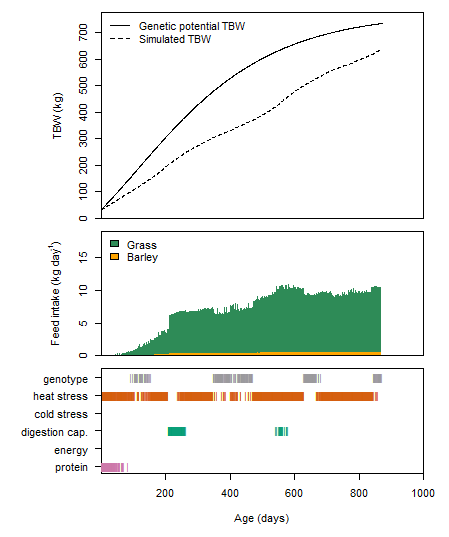
*Figure S21a.* Total body weight (TBW), feed intake, and the factors that define and limit growth of ¾ Brahman × ¼ Shorthorn reproductive cows in France. Results correspond to case 7, FQlty B×S Fr. Cows are housed in stables from December to March, and are grazing from April to November. The diet consists of 5% barley and 95% hay (December-March) and 5% barley and 95% grass (April-November). Beef production = 280 kg; FE = 31 g beef kg-1 DM feed.



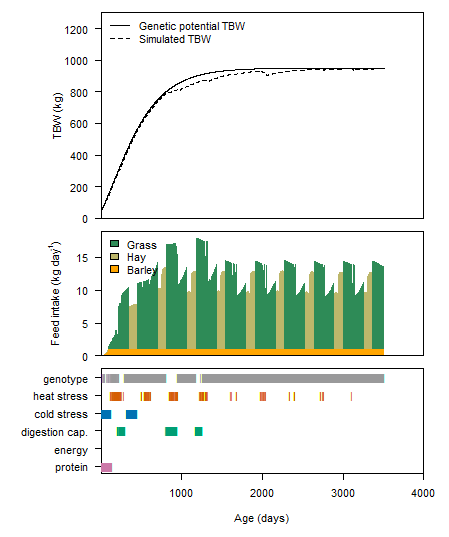
*Figure S21b.* Total body weight (TBW), feed intake, and the factors that define and limit growth of a ¾ Brahman × ¼ Shorthorn bull calf in France. Results correspond to case 7, FQlty B×S Fr. Calves are housed in stables from December to March, and are grazing from April to November. The diet consists of 5% barley and 95% hay (December-March) and 5% barley and 95% grass (April-November). Slaughter weight = 575 kg TBW; Beef production = 289 kg; FE = 107 g beef kg-1 DM feed.



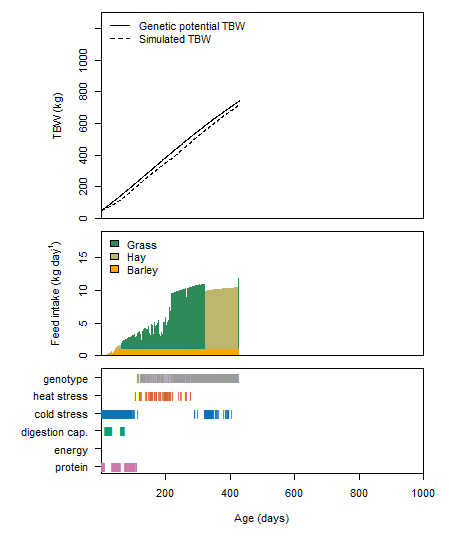
*Figure S22a.* Total body weight (TBW), feed intake, and the factors that define and limit growth of ¾ Brahman × ¼ Shorthorn reproductive cows in Australia. Results correspond to case 8, FQlty B×S Au. Cows are grazing year-round. The diet consists of 5% barley and 95% grass. Beef production = 228 kg; FE = 23 g beef kg-1 DM feed.



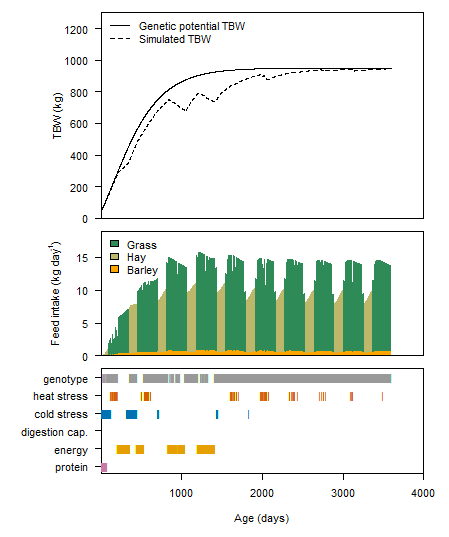
*Figure S22b.* Total body weight (TBW), feed intake, and the factors that define and limit growth of a ¾ Brahman × ¼ Shorthorn bull calf in Australia. Results correspond to case 8, FQlty B×S Au. Cows are grazing year-round. The diet consists of 5% barley and 95% grass. Slaughter weight = 638 kg TBW; Beef production = 337 kg; FE = 57 g beef kg-1 DM feed.



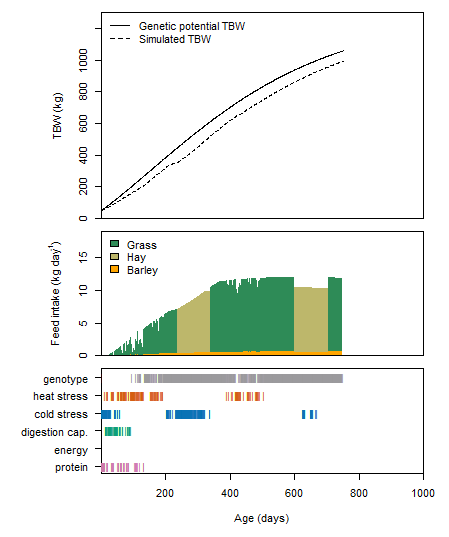
*Figure S23a.* Total body weight (TBW), feed intake, and the factors that define and limit growth of reproductive Charolais cows in France. Results correspond to case 9, FQlty Ch Fr 1 kg. Cows are housed in stables from December to March, and are grazing from April to November. The diet consists of barley, hay (December-March), and grass (April-November). Barley is maximum 65% of the diet, or maximum 1 kg DM day-1. The remaining part of the diet is hay or barley. Beef production = 476 kg; FE = 34 g beef kg-1 DM feed.



*Figure S23b.* Total body weight (TBW), feed intake, and the factors that define and limit growth of a Charolais bull calf in France. Results correspond to case 9, FQlty Ch Fr 1 kg. Calves are housed in stables from December to March, and are grazing from April to November. The diet consists of barley, hay (December-March), and grass (April-November). Barley is maximum 65% of the diet, or maximum 1 kg DM day-1. The remaining part of the diet is hay or barley. Slaughter weight = 717 kg TBW; Beef production = 348 kg; FE = 127 g beef kg-1 DM feed.



*Figure S24a.* Total body weight (TBW), feed intake, and the factors that define and limit growth of reproductive Charolais cows in France. Results correspond to case 10, FQlty Ch Fr 2%. Cows are housed in stables from December to March, and are grazing from April to November. The diet consists of 5% barley and 95% hay (December-March), or 5% barley and 95% grass (April-November). Feed availability is 2% of the TBW. Beef production = 397 kg; FE = 28 g beef kg-1 DM feed.



*Figure S24b.* Total body weight (TBW), feed intake, and the factors that define and limit growth of a Charolais bull calf in France. Results correspond to case 10, FQlty Ch Fr 2%. Calves are housed in stables from December to March, and are grazing from April to November. The diet consists of 5% barley and 95% hay (December-March), or 5% barley and 95% grass (April-November). Feed availability is 2% of the TBW. Slaughter weight = 992 kg TBW; Beef production = 523 kg; FE = 91 g beef kg-1 DM feed.

(Blaxter and Wainman, 1964, Holmes and McLean, 1975, MAFF, 1986, Kolver, 2000)

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# Appendix I Weather data

*Introduction*

This appendix aims to give information how weather files for the thermoregulation sub-model are constructed. The files have the same structure as the weather files used for crop growth models (PPS, 2016). The weather files used in this model and in crop growth models require daily data on Julian day of the year, solar radiation, solar radiation levels, minimum temperature, maximum temperature, vapour pressure, wind speed, and precipitation (Table S1). In addition, the weather files used for this livestock model require cloud cover and a conversion factor for solar radiation from a horizontal surface to coat surface. Cloud cover and conversion of solar radiation are calculated from Julian day of the year, solar radiation levels on a horizontal surface, minimum and maximum temperature, and vapour pressure. Other data required are the latitude (in degrees) and altitude of the location (in meters above sea level, MASL).

*General calculations*

As animals are represented as cylinders in McGovern and Bruce (2000) and Turnpenny *et al.* (2000), without a head and tail, the azimuth of an animal ranges from 0° up to 90°. The azimuth of an animal is assumed to be on average 45°. The size ratio of an animal is assumed to be fixed at 7.28 (2 × cylinder length / cylinder diameter) (McGovern and Bruce, 2000). The solar constant is 1367 Wm-2, and the atmospheric pressure at sea level is 101.325 kPa. The empirical turbidity coefficient for the atmosphere in rural areas is assumed to be 1.00 (Allen *et al.*, 2006).

The atmospheric pressure at sea level is corrected for the altitude of the location (Eq. A1).

[S5, 14]

Where ATM is the atmospheric pressure of the location in kPa, ATMS is the atmospheric pressure at sea level in kPa, and alt is the altitude of the location in meters above sea level. The relative distance from the earth to the sun calculated from the Julian day of the year (Eq. A2).

Where dES is the relative distance from the earth to the sun (dimensionless) and DOY is the Julian day of the year. The declination angle and hour angel of the sun are calculated according to McGovern and Bruce (2000). The hour angle is calculated for each 15 minutes (96 times per day). The depth of precipitable water in the atmosphere is calculated from Allen *et al.* (2006) (Eq. A3).

Where PW is the precipitable water in the atmosphere in mm, and VPR is the vapour pressure in kPa. Subsequently, the following variables are calculated for each day in the weather file, and for each 15 minutes within a day.

1. The cosine of the solar angle at a horizontal surface
2. Solar radiation at a horizontal surface
3. The clearness index for the direct solar radiation beam (Allen *et al.*, 2006)
4. The index for diffuse beam radiation (Allen *et al.*, 2006)
5. Direct and diffuse solar radiation at a horizontal surface

The cosine of the solar angle at a horizontal surface is given in Eq. A4.

Where coshor is the cosine of the solar angle at a horizontal surface, t is an 15 minute interval within a day, decl is the solar declination angle at a specific Julian day, LAT is the latitude in ° (positive for the northern hemisphere; negative for the southern hemisphere), decl is the declination angle at a specific Julian day, and HOUR is the hour angle at a specific moment of the day. To calculate the maximum solar radiation at a horizontal surface, the negative cosine values for the solar angle (*i.e.* between sunset and sunrise) are set to zero (Eq. A5).

Where Rad is the solar radiation intercepted by the atmosphere of the earth in Wm‑2, and SOLCONST is the solar constant. Next, the clearness index for the direct beam is calculated (Eq. A6).

Where KBo is clearness index for the direct beam, and TURB is the turbidity coefficient. The index for diffuse beam radiation is calculated based on Allen *et al.* (2006). The maximum solar radiation intercepted by the earth’s surface is calculated from the solar radiation intercepted by the earth’s atmosphere and the indices for direct and diffuse beams (Eq. A7).

Where Rso is the maximum solar radiation intercepted by the earth’s surface in Wm-2. The maximum solar radiation per day is calculated as the average solar radiation in W m-2 for the 15 minute intervals, and is subsequently converted from Wm-2 to kJ m‑2 day-1.

*Calculation of cloud cover*

Actual solar radiation on a horizontal surface is adopted from the file with weather data (Table S1). The ratio actual : maximum solar radiation intercepted on a horizontal surface can be used to calculate cloud cover. Eq. A8 was fitted based on data of Lane (1989). This formula is based on data from the North Sea area, but it is assumed to be applicable worldwide.140}

Where CC is cloud cover in Ω (*i.e.* eights), and A:M is the ratio actual : maximum solar radiation intercepted. Values lower than zero are set at zero, and values higher than eight are set to eight.

*Calculation of solar radiation on an animal’s coat*

For conversion of solar radiation on a horizontal surface to coat surface, the following variables are calculated for each day in the weather file, and for each 15 minutes within a day.

1. Solar elevation above the horizon (Eq. A9)
2. Solar azimuth (Eq. A10)
3. Difference between solar azimuth and animal azimuth (Eq. A11)
4. Conversion factor solar radiation on horizontal surface to coat (Eq. A12)
5. Sinus of solar radiation at a horizontal surface
6. Sinus of solar radiation at an animal’s coat

Where solelev is the solar elevation above the horizon, and LAT is the latitude of the location.

Where azim is the solar azimuth.

Where dazim is the difference solar azimuth and animal azimuth, and ANAZIM is the azimuth of the animal. The conversion factor for solar radiation on horizontal surface to coat is zero between sunset and sunrise. Eq. A12 applies between sunrise and sunset (McGovern and Bruce, 2000).

Where CFR is the dimensionless conversion factor solar radiation on horizontal surface to coat, and SRAN is the size ratio of the animal. The sinus of solar radiation at a horizontal surface is equal to the solar elevation between sunrise and sunset. This sinus of solar radiation at a horizontal surface is multiplied by the conversion factor for solar radiation on horizontal surface to coat surface, for each Julian day and for each interval of 15 minutes in a day. Subsequently, the sinus of solar radiation at a horizontal surface, and the sinus of solar radiation at an animal are summed. The daily conversion factor for solar radiation on a horizontal surface to coat surface is the daily sum of the sinus at an animal divided by the daily sum of the sinus at a horizontal surface. Finally, this conversion factor is multiplied by the measured solar radiation on a horizontal surface from the weather file (Table S1), to assess the heat load from solar radiation at an animal’s coat surface.

*Model comparison*

The solar angles (Eq. A4) and maximum theoretical solar radiation (Eq. A7), expressed in kJ m-2 day-1, are key to calculate cloud cover and solar radiation on an animal’s coat. The hypothesis is that measured solar radiation is close to the maximum theoretical solar radiation at clear days, but at cloudy days the measured solar radiation will be below the maximum theoretical solar radiation. We compared measured solar radiation of various countries with the maximum theoretical solar radiation to test this hypothesis (Table A1).

*Table A1.* Overview of countries and locations to compare the maximum theoretical solar radiation with measured data.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Country | Location | Years | Latitude | Altitude (MASL) | Intrapolation1 |
| The Netherlands | Wageningen | 1998-2000 | 51.97 °N | 9 | No |
| France | Charolles | 1998-2000 | 46.44 °N | 290 | No |
| Ethiopia | Arba Minch | 1998-2000 | 6.03 °N | 1285 | Yes |
| Australia2 | Kununurra | 1992 | 15.77 °S | 47 | No |
| Zambia | Mazabuka | 2008-2010 | 15.87 °S | 1050 | Yes |
| New Zealand | Invercargill | 2005-2008 | 46.41 °S | 11 | No |

MASL = meters above sea level

1 Weather data are not measured on the location, but calculated from intrapolated data from surrounding stations.

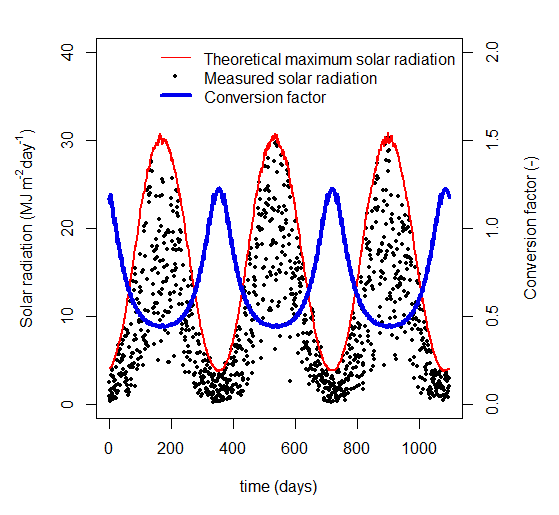
2 Daily vapour pressure data in Kununurra, Australia were not available.

In addition, the simulated cloud cover was compared to the measured cloud cover from de Bilt, the Netherlands (52.11 °N, altitude 1.9 meters above sea level), for the years 2014-2015. Cloud cover was simulated based on measured solar radiation, minimum and maximum temperature, and vapour pressure. Simulated cloud cover is given as continuous numbers, whereas measured cloud cover is given as integers.

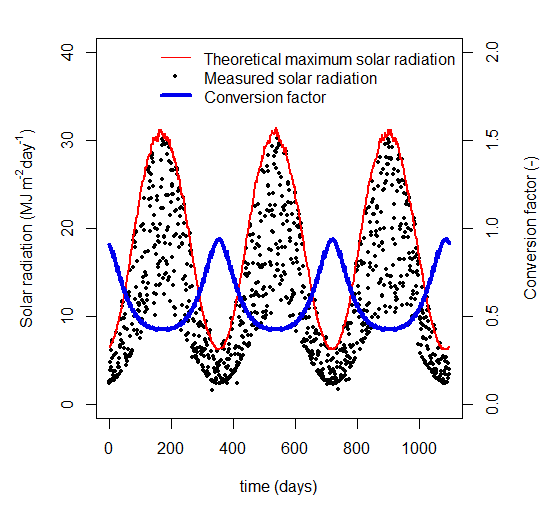
*Results and discussion*

The theoretical maximum solar radiation levels are close to the highest values for the measured solar radiation levels throughout the year. The agreement between the theoretical maximum solar radiation level and the highest measured solar radiation level was very good for weather data from the Netherlands, France, and New Zealand (Figs A1, A2, and A6). Intrapolated weather data were used for the locations in Ethiopia and Zambia (Figs A3 and A5), which are generally considered of lower quality than measured weather data on the locations. This may explain why there is less agreement between the theoretical maximum and the intrapolated solar radiation data. For Australia, the theoretical maximum solar radiation data are a bit irregular, with a sharp increase on Julian day 91 and a sharp decrease on Julian day 336 (Fig. A4). This is explained by the difference in vapour pressure between Julian day 91 up to 336, the dry season, and the rest of the year, the wet season. Vapour pressure was not available at a daily basis, but only per season.

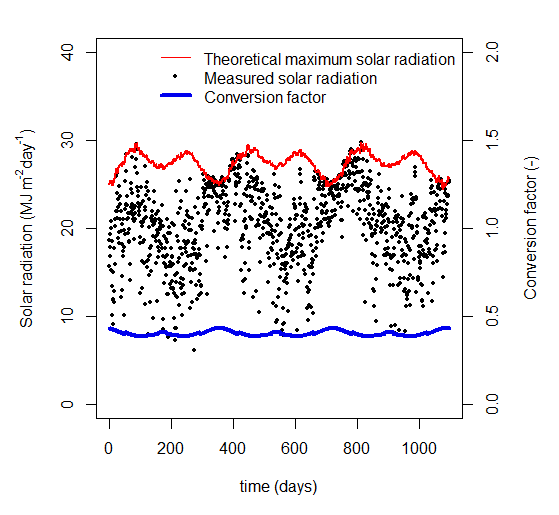
The conversion factor from solar radiation on a horizontal surface to solar radiation at an animal’s coat has a minimum value of 0.4 at the equator (Fig. A3). This corresponds to conditions where the solar elevation is 90 °C, and is passing zenith. The conversion factor is lower than one, because the area of the cylinder that represents the animal is much larger than the area that is intercepting the solar radiation. The conversion factor is high during winter in locations with high latitudes in the northern hemisphere and locations with low latitude in the southern hemisphere (Figs A1 and A6). This is because solar elevation in winter in temperate regions is relatively low, and solar radiation per unit of horizontal surface area is low. The cylinder representing an animal, can still intercept the solar radiation that is almost parallel to the horizontal surface.



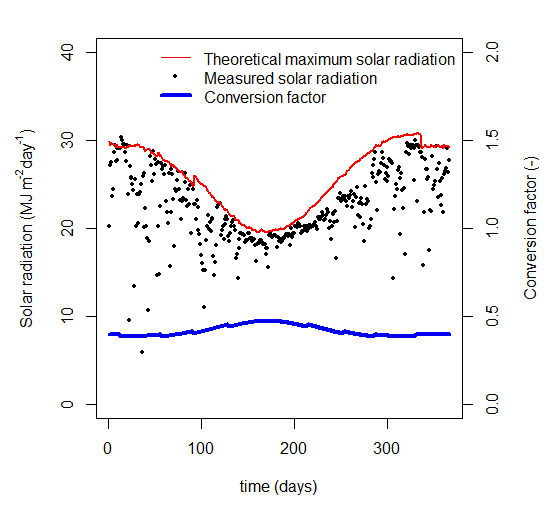
*Figure A1.* Theoretical maximum and measured solar radiation levels, and the conversion factor from solar radiation at a horizontal surface to the coat of beef cattle. Weather data are from Wageningen, the Netherlands (51.97 °N, altitude 9 m), for the years 1998-2000.



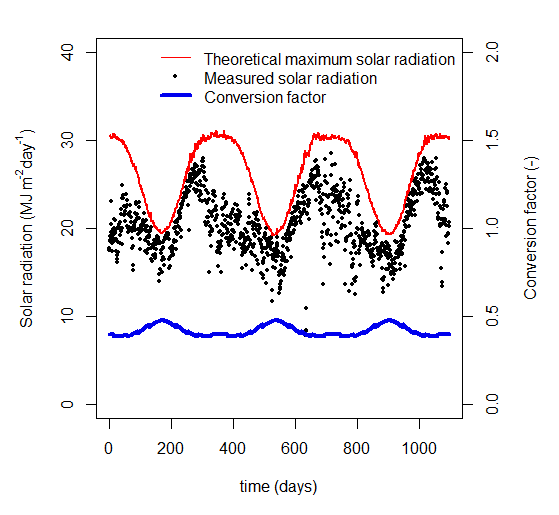
*Figure A2.* Theoretical maximum and measured solar radiation levels, and the conversion factor from solar radiation at a horizontal surface to the coat of beef cattle. Weather data are from Charolles, France (46.44 °N, altitude 290 m), for the years 1998-2000.



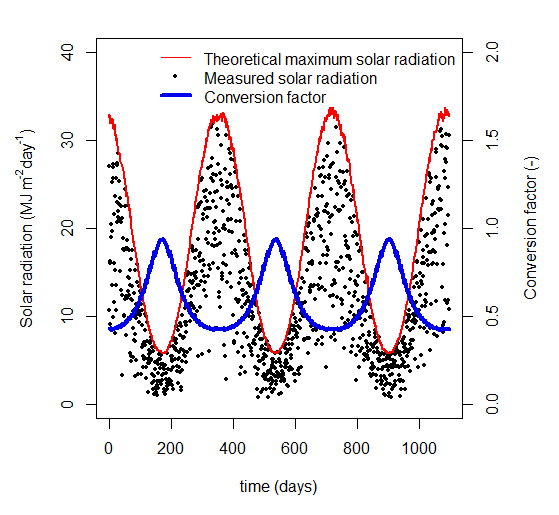
*Figure A3.* Theoretical maximum and measured solar radiation levels, and the conversion factor from solar radiation at a horizontal surface to the coat of beef cattle. Intrapolated weather data are from Arba Minch, Ethiopia (6.03 °N, altitude 1285 m), for the years 1998-2000.



*Figure A4.* Theoretical maximum and measured solar radiation levels, and the conversion factor from solar radiation at a horizontal surface to the coat of beef cattle. Weather data are from Kununurra, Australia (15.77 °S, altitude 47 m), for the year 1992.

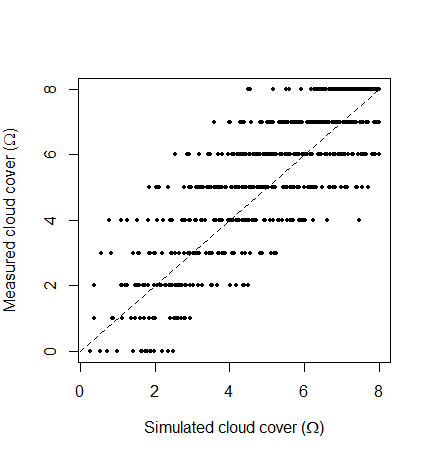


*Figure A5.* Theoretical maximum and measured solar radiation levels, and the conversion factor from solar radiation at a horizontal surface to the coat of beef cattle. Intrapolated weather data are from Mazabuka, Zambia (15.87 °S, altitude 1050 m), for the years 2008-2010.



*Figure A6.* Theoretical maximum and measured solar radiation levels, and the conversion factor from solar radiation at a horizontal surface to the coat of beef cattle. Weather data are from Invercargill, New Zealand (46.41 °S, altitude 11 m), for the years 2005-2008.

Comparison of simulated cloud cover (continuous) and measured (integers) cloud cover and showed that the mean absolute error in is 0.95 Ω, and the root mean square error is 1.23 Ω. The regression line between measured and simulated cloud cover has an R2-adj. of 0.70, but its slope and intercept are significantly different from one and zero (*P* < 0.001) (Fig. A7).



*Figure A7.* Simulated versus observed cloud cover, expressed in Ω, for the years 2014-2015 in de Bilt, the Netherlands (52.11 °N, altitude 1.9 meters above sea level). The dashed line is the 1:1 line.

*Conclusion*

In conclusion, the theoretical maximum solar radiation and the highest measured solar radiation levels are in agreement for several locations around the world. The value of the conversion factor from horizontal surface area to an animal’s coat seem to be reasonable. Cloud cover data calculated with this methodology can be used under the assumption that there is a linear relation between the ratio measured solar ration to maximum solar radiation and cloud cover (mean absolute error was 0.95 Ω in the Netherlands).

*Use of software*

The calculations above are included in the file ‘Weatherfilesynthesis20151208.R’. The script of the weather files requires three inputs:

* The latitude of the location in degrees, with negative values for the southern hemisphere (line 22).
* The altitude of the location in meters above sea level (line 23).
* Input weather files must be structured in the same way as the weather files found on the model portal of the Plant Production Systems group of Wageningen University, the Netherlands (<http://models.pps.wur.nl/node/1062>). The directory and name of the original input file have to be specified (line 26).
* The directory of the new file with data on solar radiation on the coat and cloud cover must be specified also (line 27).

After supplying the input specified and running the source code, a new weather file with the conversion factor for solar radiation on the coat and with cloud cover is stored in the directory specified for the new file.

# Appendix II Source code: structure and description

This Appendix briefly describes the contents of LiGAPS-Beef. The source code consists of an initial, dynamic, and an output section. The initial section is indicated by a 1 in the source code, the dynamic section by a 2, and the output section by a 3. Section and sub-section numbers below are the same as in the source code. The source code of LiGAPS-Beef consists of 2806 rules (some are left blank). The description below indicates the rule numbers (r.) also.

r. 1-125 General information and input data for cases listed in Table 3 of the main paper and sensitivity analysis. This part can be adapted for other modelling objectives.

r. 1-68 Model title and general information

r. 69-127 Input data for the cases listed in Table 3 of the main paper.

r. 128-154 Code to perform sensitivity analysis (not used in the version LiGAPSBeef20160922\_herd.R)

r. 154-1526 1. Initial section with model parameters and initial values of variables

r. 166-223 1.1 Description of the farming system, with the location, breeds used, housing, cattle management, and the level of the simulation (animal or herd level

r. 224-272 1.2 Weather data, selected based on the location, and adapted to the housing conditions

r. 273-797 1.3 Input parameters

r. 277-413 1.3.1 Breed- and sex specific parameters (listed in Table S2)

r. 414-587 1.3.2 Parameters for feed intake and digestion (listed in Table S3 and S4). Feed availability and feed types are specified in this part.

r. 588-797 1.3.3 General parameters used in physics and chemistry (r. 597-628, listed in Table S5), and general parameters for cattle (r. 629-789, listed in Table S6).

r. 798-1353 1.4 Specification of variables

r. 802-883 1.4.1 Variables used in the feed intake and digestion sub-model

r. 884-982 1.4.2 Variables used in the thermoregulation sub-model

r. 983-1155 1.4.3 Variables used in the energy and protein utilisation sub-model

r. 1156-1212 1.4.4 Variables used to integrate the three sub-models

r. 1213-1326 1.4.5 Variables to scale up from animal to herd level, and miscellaneous variables

r. 1327-1353 Feed availability over time

r. 1354-1526 1.5. Initial values of variables for animals

r. 1527-3498 2. Dynamic section

r. 1532-1983 2.1 Thermoregulation sub-model

r. 1546-1858 2.1.1 Maximum heat release

r. 1859-1983 2.2.2 Minimum heat release

r. 1984-2413 2.2 Energy and protein utilisation sub-model

r. 1988-2147 Energy and protein requirements for genetic potential growth

r. 2148-2164 Energy and protein requirements for maintenance

r. 2165-2181 Energy and protein requirements for physical activity

r. 2182-2293 Energy and protein requirements for gestation

r. 2294-2351 Energy and protein requirements for lactation

r. 2352-2413 Energy and protein requirements for growth

r. 2414-2472 2.3 Feed intake and digestion sub-model. This part considers the maximum feed digestion capacity. More source code on feed intake and digestion is given in section 2.4 on the integration of sub-models.

r. 2473-3498 2.4 Integration of sub-models

r. 2477-2572 Initial values of variables for integration of sub-models

r. 2573-2710 Feed intake and digestion sub-model

r. 2711-2717 Additional energy and protein requirements under heat stress

r. 2718-2775 Energy and protein requirements for growth, simulation of heat production

r. 2776-3033 Integration of the heat balance and net energy balance

r. 3034-3094 Growth affected by heat and cold stress, and tissue dissimilation under sub-maintenance feeding

r. 3095-3231 Rules to determine whether animals are taken from the herd unit (culling and slaughter)

r. 3232-3270 Calculation of total feed intake and feed efficiency

r. 3271-3467 Upscaling from animal to herd level, results in weather files for the calves, and calculates beef production and feed intake per herd unit

r. 3468-3498 Parameter list for sensitivity analysis (not used in the version LiGAPSBeef20160922\_herd.R)

r. 3499-3833 3. Output section. The output represented in figures and tables must be tailored to the research objective.

r. 3503-3659 Graph for the reproductive cow in a herd unit

r. 3660-3813 Graph for bull calves in a herd unit

r. 3814-3831 Table with key information on cattle performance. The information in this table corresponds with the information in Table 3 of the main paper.

# Appendix III Source code: loops

This appendix lists the various loops used in LiGAPS-Beef, as given in the file LiGAPSBeef20160922\_herd.R. Loops allow to repeat parts of the programme code multiple times with different input data. The loop indicated with a ‘z’ in the source code simulates the different cases provided in Table 1 of the main paper. Model users can adapt this loop for different purposes. The loop indicated with an ‘s’ in the source code was used for sensitivity analysis. Only the standard parameters are used in the given version of LiGAPS-Beef, and code is not repeated for parameters decreased or increase in value. Loops indicated with an ‘i’ simulate over time, with i being the ith time step. The loop indicated with an ‘j’ simulates the animals in a herd unit, with j being the jth animal in a herd unit. If LiGAPS-Beef is run at animal level, there is one animal in the j loop, and no repetition occurs.

The list below indicates the line numbers (r.) where loops start and end. A start of a loop is indicated with an opening brace, and an end with a closing brace, just as in the R programming language.

r. 125 z loop for cases {

r. 155 s loop for sensitivity analysis {

r. 249 i loop for weather data over time {

r. 259 i loop for weather data over time}

r. 508 i loop for feed types and quantities over time {

r. 569 i loop for feed types and quantities over time }

r. 1340 j loop for animals in a herd unit {

r. 1349 i loop over time {

r. 1745 repeat loop for maximum heat release {

r. 1857 repeat loop for maximum heat release }

r. 1903 repeat loop for minimum heat release {

r. 1982 repeat loop for minimum heat release }

r. 2497 repeat loop for integration of sub-models {

r. 2992 repeat loop for integration of sub-models {

r. 3270 i loop over time }

r. 3346 j loop for animals in a herd unit }

r. 3387 p loop for probability calculations herd unit {

r. 3409 p loop for probability calculations herd unit }

r. 3466 s loop for sensitivity analysis }

r. 3833 z loop for cases }

# Appendix IV Source code LiGAPS-Beef

This appendix contains the source code of the complete model LiGAPS-Beef in the file named LiGAPSBeef20180301\_herd.R. The source code reproduces the results for case 1, 3, 5, 7, 9 and 10 at herd level, which are listed in Table 1 and 3 of the main paper (Van der Linden *et al.*, 2018a). The code also reproduces the figures in Chapter 2.2 associated with these cases (S17, S18, S20, S21, S23, S24).

#######################################################################################

#

# LiGAPS-Beef

# (Livestock simulator for Generic analysis of Animal Production Systems-Beef cattle)

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#

#

# The model LiGAPS-Beef is described in the paper:

# LiGAPS-Beef, a mechanistic model to explore potential and feed-limited beef

# production: 1. Model description and illustration.

# Authors: A. van der Linden 1,2,\*, G.W.J. van de Ven 2, S.J. Oosting 1,

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#

#

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#

# LiGAPS-Beef aims to simulate potential and feed-limited production for beef

# production systems across the world. Potential and feed-limited production are used

# to calculate the yield gap, which is the difference between actual and potential or

# feed-limited production. In addition, the model identifies the defining and

# limiting factors for growth and production of beef cattle.

#

# Description program code:

# This program code contains the model LiGAPS-Beef, including its thermoregulation

# sub-model, its feed intake and digestion sub-model, and its energy and protein

# utilisation sub-model.

#

# This specific version of LiGAPS-Beef is used to illustrate the model for ten

# different cases which are described in the section 'Model illustration' in the

# paper of Van der Linden et al. The cases are described in Table 1, and model

# results at herd level are given in Table 3. Figure 5 presents the defining and

# limiting factors for growth. This model was developed during the PhD project

# 'BenchmarkingAnimal Production Systems', 2012-2016.

#

# The PhD project was part of the Dutch IPOP project: 'Mapping for sustainable

# intensification'

# http://www.wageningenur.nl/en/About-Wageningen-UR/Strategic-plan/Mapping-for-

# Sustainable-Intensification.htm

#

# Last update: 01-03-2018

#

#######################################################################################

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# Code for model illustration #

#######################################################################################

# The vectors below indicate the parameters for the ten cases presented in Table 1 of

# the paper.

ill.genotype <- c(1,1,4,4,1,1,4,4,1,1) # Genotype or breed used; 1 = Charolais,

# 4 = 3/4 Brahman x 1/4 Shorthorn

# Optimum slaughter weight of bull calves to maximize feed efficiency for each of the

# ten cases in Table 3.The slaughter weight is optimized to maximize the feed

# efficiency at the herd level.

ill.slweight <- c(936.1493, 717.3103, 579.8809, 559.7907, 877.8683, 460 , 574.7075,

638.0943, 717.469, 992.1554)

# Locations: FRANCE1 = Charolles, France (46.4??N, 4.3??E); AUSTRALIA1 = Kununurra,

# Australia (15.7??S, 128.7??E)

ill.location <- c("FRANCE1","AUSTRALIA1","FRANCE1","AUSTRALIA1","FRANCE1",

"AUSTRALIA1","FRANCE1","AUSTRALIA1","FRANCE1","FRANCE1")

# Cattle in France are kept indoors from December to March, and outdoors from April

# to November. Cattle in Australia were kept outdoors year-round.

# Search for ill.housing for how this code is used.

ill.housing1 <- c(0,1,0,1,0,1,0,1,0,0) # Housing 0 = housed in a stable; 1 = outdoors

ill.housing2 <- c(1,1,1,1,1,1,1,1,1,1) # Housing 0 = housed in a stable; 1 = outdoors

ill.housing3 <- c(0,1,0,1,0,1,0,1,0,0) # Housing 0 = housed in a stable; 1 = outdoors

ill.f1 <- c(20,20,20,20,20,20,20,20, 0,(2\*0.95)) # Feed availability 1 (kg DM per

#animal per day), which represents ad libitum feeding at a value of 20 kg DM.

ill.f2 <- c( 0, 0, 0, 0, 0, 0, 0, 0,20, 0) # Feed availability 2 (kg DM per animal per

# day), which indicates that this feed type is not available, except for the nineth

# case (barley).

FEEDNR <- c(1,1,1,1,2,3,2,3,4,5) # Diet numbers

# 1 = 65% wheat and 35% good quality hay (diet under potential production, van der

# Linden et al. (2015))

# 2 = 5% barley and 95% grass (France) or hay, depending on whether the animals are

# housed or not

# 3 = 5% barley and 95% grass (Australia)

# 4 = 1 kg DM barley per day, rest of the diet is grass (France) or hay

# 5 = 5% barley and 95% grass (France) or hay, depending on whether the animals are

# housed or not, at most of 2% of the total body weight per day

GENLIMdata <- c(rep(NA,4000)) # vector to record days when the animal's genotype

# is the most defining factor for growth

HEATSTRESSdata <- c(rep(NA,4000)) # vector to record days when heat stress (climate)

# is the most defining factor for growth

COLDSTRESSdata <- c(rep(NA,4000)) # vector to record days when cold stress (climate)

# is the most defining factor for growth

FILLGITGRAPHdata <- c(rep(NA,4000)) # vector to record days when digestion capacity

# (feed quality) is the most limiting factor

# for growth

NELIMdata <- c(rep(NA,4000)) # vector to record days when energy deficiency is

# the most limiting factor for growth

PROTGRAPHdata <- c(rep(NA,4000)) # vector to record days when protein deficiency is

# the most limiting factor for growth

for (z in c(1,3,5,7,9:10)) { # z-loop for each of the cases in France. Number refer to

# the numbers of the cases simulated (Table 1).

#######################################################################################

# Sensitivity analysis (one-at-a-time approach) #

#######################################################################################

# Source code for sensitivity analysis (not used for model illustration). Sensitivity

# analyis is conducted in the second paper: LiGAPS-Beef, a mechanistic, model to

# explore potential and feed-limited beef production 2. Sensitivity analysis and

# evaluation of sub-models (Van der Linden et al.)

# Settings for sensitivity analysis (par. 119 is the base scenario)

# s indicates the sensitivity loop

NPAR = 118 # number of parameters in sensitivity analysis

NPAR = NPAR + 1 # number of parameters plus includes reference scenario

RELDIFF = -0.10 # relative increase or decrease of parameters (fraction)

SENSDAT <- c(rep(c(1,rep(0,NPAR)),(NPAR-1)),1)

SENSMAT <- matrix(nrow=NPAR, ncol=NPAR, data = (SENSDAT \* RELDIFF+1))

SENSMAT[119,119] <- 1.0 # parameters in reference scenario are not changed

SENSMAT <- SENSMAT[1:NPAR,]

FESENSREPR <- c(rep(0,NPAR)) # Matrix indicating the feed efficiency of the

# reproductive cow

FESENSIND <- c(rep(0,NPAR)) # Matrix indicating the feed efficiency of the bull

# (calf)

FESENSHERD <- c(rep(0,NPAR)) # Matrix indicating the feed efficiency of the herd unit

for(s in 119){ # s-loop for the parameters included in the sensitivity analysis.

# Run number 119 is the base scenario used to calculate the relative change in model

# output.

starttime <- proc.time() # Start processing time

#####################################################################################

# 1. Initial section #

#####################################################################################

#####################################################################################

# 1.1 Farming system description #

#####################################################################################

# The beef production system is described in this section of the model

# Genotype (i.e. breed), location, and scale (animal or herd level)

BREED = ill.genotype[z] # Breed (1 = Charolais; 2 = Boran; 3 = Parda de

# Montana; 4 = Brahman (3/4) x Shorthorn (1/4); 5 =

# Hereford (only steers)

LOCATION <- ill.location[z] # See ill.location for the geographical location.

SCALE = 2 # Scale/level of the system (1 = individual animal/the

# animal level; 2 = herd unit/herd level) For

# simulations at the animal level, see the results in

# Table 2 of the paper.

SEX\_ANIMAL = 0 # Animal sex (0 = male; 1 = female), only for

# simulations at the animal level (i.e. if SCALE

# equals 1)

# Climate and housing

# Code housing: 0 = stable or feedlot, 1 = free grazing system; 2 = open feedlot

PHASE1 <- rep(ill.housing1[z],84) # Housing period 1 (indicates January - March;

# 25th of March = day 84)

PHASE2 <- rep(ill.housing2[z],260) # Housing period 2 (indicates March - December)

PHASE3 <- rep(ill.housing3[z],21) # Housing period 3 (indicates December)

# The sum of all phases should equal 365 days (1 full year)

# Changes in outdoor climate conditions to calculate indoor climate conditions:

WINDMAX = 5 # maximum wind speed (in ms-1)

RADTRANS = 0.0 # fraction of solar radiation in stable (related to roof

# construction)

WINDRED = 0.5 # fraction reduction of wind speed in stable (related to

# construction)

TINCR = 5.6667 # increase in stable temperature compared to outdoor at 0

# degrees Celsius

Tdelta = 0.8667 # increase in stable temperature per degree Celsius increase in

# outdoor temperature

# Management

# See van der Linden et al (2015) for an explanation on cattle management under

# potential and feed-limited production (Agricultural Systems 139 : 100-109).

MAXCALFNR = 8 # Number of calves per cow (max = 8; only for

# reproductive animals)

imax = 4000 # Duration of simulation (# days)

MAXFATCARC = 0.0 # Maximum fat percentage in the carcass for slaughter

# of reproductive animals (0.0 = no minimum fat

# percentage)

MAXLIFETIME = 11.36 # Maximum # years a productive animal can live

MAXCONCAGE = 10.00 # Maximum conception age of a reproductive animal

CULL = 0.5 # Culling rate (fraction reproductive cows per year),

# which equals 50% per year.

SWMALES = ill.slweight[z] # Slaughter weight male calf/calves (kg)

SWFEMALES = 390 # Slaughter weight female calf/calves (kg)

STDOY = 1 # Day of the year in which the first animal is born

#####################################################################################

# 1.2 Weather data #

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# Library with weather data (file chosen depends on LOCATION)

# Model users should ensure that the directory of the weather file and the directory

# given below correspond to each other!

if(LOCATION == "FRANCE1")

WEATHER <-read.csv(file="M:/R/FRACHA19982012.csv", head=TRUE,sep=",") else

if(LOCATION == "AUSTRALIA1")

WEATHER <-read.csv(file="M:/R/AUSTRALIA1992A.csv", head=TRUE,sep=",")

# If wind speeds are exceptionally high, these can be replaced by a maximum wind

# speed.

if(max(WEATHER$WIND) > WINDMAX) WINDHIGH <- "Yes" else WINDHIGH <- "No"

WEATHER$WIND[WEATHER$WIND > WINDMAX] <- WINDMAX # Maximum wind speed equals WINDMAX

PHASE <- c(PHASE1,PHASE2,PHASE3) # Connect all phases in one year

HOUSING <- rep(PHASE,12) # Twelve years with housing (free grazing,

# stable or feedlot) are constructed

HOUSING <- HOUSING[STDOY:length(HOUSING)] # Housing starts at the day the animal is

# born.

# Modify weather data if cattle are housed in stables or feedlots

for(i in 1:length(imax)){

# roof over stable reduces radiation levels

if(HOUSING[i] == 0) WEATHER$RAD[i] <- WEATHER$RAD[i] \* RADTRANS

# stable construction reduces wind speed

if(HOUSING[i] == 0) WEATHER$WIND[i] <- WEATHER$WIND[i] \* WINDRED

# increase in stable minimum temperature relative to outdoor temperature

if(HOUSING[i] == 0) WEATHER$MINT[i] <- Tdelta \* WEATHER$MINT[i] + TINCR

# increase in stable maximum temperature relative to outdoor temperature

if(HOUSING[i] == 0) WEATHER$MAXT[i] <- Tdelta \* WEATHER$MAXT[i] + TINCR

}

WEATHER <- WEATHER[STDOY:nrow(WEATHER),] # The weather files starts at the day the

# first animal is born

DOY <- WEATHER$DOY-floor(WEATHER$DOY/365)\*365 # Calculates day of the year (DOY) if

# days numbered ascending for multiple

# years in the weather files.

DOY[DOY==0] <-365 # For simplicity, one year is assumed

# to have 365 days per year instead of

# 365.24 days per year

WEATHERORIG <- WEATHER # Creates a copy of the weather data file

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# 1.3 Parameters #

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###########################################################################################

# 1.3.1 Genetic parameters (related to BREED and SEX) #

###########################################################################################

# This section contains a list of 26 genetic parameters (a LIBRARY) which are specific for

# the genotype (i.e. breed) and sex. Numbers before the parameter description refer to the

# order of parameters in the LIBRARY, which is not the same as in the Supplementary

# Material. Numbers after the parameter description [between brackets] refer to the

# parameter numbers in Table S2 of the Supplementary Material.

# 1 reflectance coat [5]

# 2 coat length [3]

# 3 body area (body area : weight factor) [1]

# 4 maximum cond. body core ??? skin [4]

# 5 birth weight [9]

# 6-10 parameters of the Gompertz curve [9-12,19]

# 11-12 lactation curve parameters A and B (A = 0, no milk production male) [13,14]

# 13 adult max. weight [20]

# 14 sex (0= male, 1 = female)

# 15-16 lactation curve parameters A and B (milk available for calf) [13,14]

# 17 minimum fraction mature TBW for gestation [21]

# 18 maintenance correction factor [17]

# 19 minimum fat tissue % in carcass for gestation [22]

# 20 lipid bone parameter [16]

# 21 maximum carcass fraction [18]

# 22 maximum muscle:bone ratio [19]

# 23 minimum conduction body core ??? skin [4]

# 24-26 latent heat release 1,2, and 3 [6-8]

# 27 lactation curve parameter C [15]

# Parameters for Charolais bulls Parameter number

LIBRARY10 <- c(0.60, 0.012, 1.00 , 64.1, 48.1, # 1-5

1616.7, 48.1, 1.6, 1.10, 316.7, # 6-10

0.0000, 0.068, 1300, 0, 8, 0.068, # 11-16

0.60, 1.0, 0.32, # 17-19

11.1, 0.64, 4.4, 1.00, # 20-23

3.08, 1.73, 35.3, 0.00338) # 24-27

# Parameters for Charolais heifers / cows Parameter number

LIBRARY11 <- c(0.60, 0.012, 1.00, 64.1, 45.9, # 1-5

1178.7, 45.9, 1.6, 1.10, 228.7, # 6-10

8, 0.068, 950, 1, 8, 0.068, # 11-16

0.60, 1.0, 0.32, # 17-19

11.8, 0.62, 4.1, 1.00, # 20-23

3.08, 1.73, 35.3, 0.00338) # 24-27

# Parameters for Boran bulls Parameter number

LIBRARY20 <- c(0.60, 0.012, 1.12, 64.1, 28.0, # 1-5

608.7, 28.0, 4.2, 1.5, 8.7, # 6-10

0.0000, 0.150, 600, 0, 0.5510, 0.150, # 11-16

0.55, 0.91, 0.32, # 17-19

13.3, 0.578, 4.1, 1.30, # 20-23

4.89, 0.80, 34.5) # 24-27

# Parameters for Boran heifers / cows Parameter number

LIBRARY21 <- c(0.60, 0.012, 1.12, 64.1, 25.0, # 1-5

456.5, 25.0, 4.2, 1.5, 6.5, # 6-10

0.5510, 0.150, 450, 1, 0.5510, 0.150, # 11-16

0.55, 0.91, 0.32, # 17-19

14.3, 0.55, 3.60, 1.30, # 20-23

4.89, 0.80, 34.5) # 24-27

# Parameters for Parda de Montana bulls Parameter number

LIBRARY30 <- c(0.56, 0.012, 1.00 , 64.1 , 42.0, # 1-5

1308.4, 42.0, 1.6, 1.15, 255.7, # 6-10

0.00, 0.150, 1052.7, 0, 0.46, 0.150, # 11-16

0.55, 1.0, 0.32, # 17-19

11.6, 0.64, 4.8, 1.00, # 20-23

3.08, 1.73, 35.3) # 24-27

# Parameters for Parda de Montana heifers / cows Parameter number

LIBRARY31 <- c(0.56, 0.012, 1.00, 64.1, 40.0, # 1-5

769.3, 40.0, 1.6, 1.10, 147.3, # 6-10

0.4562, 0.150, 622, 1, 0.4562, 0.150, # 11-16

0.55, 1.0, 0.32, # 17-19

12.9, 0.62, 4.3, 1.00, # 20-23

3.08, 1.73, 35.3) # 24-27

# Parameters for 3/4 Brahman x 1/4 Shorthorn steers/bulls Parameter number

LIBRARY40 <- c(0.56, 0.012, 1.09 , 64.1 , 33.0, # 1-5

962.6, 33.0, 1.6, 1.50, 187.6, # 6-10

0.0000, 0.068, 775, 0, 5.68, 0.068, # 11-16

0.50, 0.93, 0.32, # 17-19

11.6, 0.5935, 4.1, 1.225, # 20-23

3.08, 2.15, 35.6, 0.00338) # 24-27

# Parameters for 3/4 Brahman x 1/4 Shorthorn heifers Parameter number

LIBRARY41 <- c(0.56, 0.012, 1.09 , 64.1 , 30.0, # 1-5

744.2, 30.0, 1.6, 1.50, 144.2, # 6-10

5.68, 0.068, 675, 1, 5.68, 0.068, # 11-16

0.50, 0.93, 0.20, # 17-19

11.6, 0.55, 3.6, 1.225, # 20-23

3.08, 2.15, 35.6, 0.00338) # 24-27

# Parameters for Hereford steers/bulls Parameter number

LIBRARY50 <- c(0.44, 0.012, 1.00 , 64.1 , 41.0, # 1-5

1054.6, 41.0, 1.6, 0.99, 204.6, # 6-10

0.0000, 0.150, 850, 0, 0.300, 0.150, # 11-16

0.55, 1.00, 0.32, # 17-19

11.6, 0.60, 4.275, 1.00, # 20-23

3.08, 1.73, 35.3) # 24-27

# Parameters for Hereford heifers Parameter number

LIBRARY51 <- c(0.44, 0.012, 1.00 , 64.1 , 36.9, # 1-5

768.95, 36.9, 1.6, 0.99, 147.8, # 6-10

0.4561, 0.150, 621.15, 1, 0.300, 0.150, # 11-16

0.55, 1.00, 0.20, # 17-19

11.6, 0.57, 4.0, 1.00, # 20-23

3.08, 1.73, 35.3) # 24-27

###########################################################################################

# Simulations with individual cows do not include calf birth

if(SCALE== 1) MAXCALFNR <- 0 else MAXCALFNR <- MAXCALFNR

# Sex of the calves of the reproductive cow (1= female; 0=male)

# The first number indicates the male calf. This sequence is only valid at a culling rate

# of 50% per cow per year (van der Linden et al, 2015. Agricultural Systems 139 : 100-109)

SEX\_CALVES <- c(1,0,0,0,0,0,0,0,0,0,0,0,0) # Sex reproductive cow + offspring

# (1= female; 0=male)

if(SCALE== 1) SEX <- SEX\_ANIMAL else SEX <- c(1,SEX\_CALVES)

jmax <- MAXCALFNR + 1 # Number of animals in the simulation at the animal level or the herd

# level

# Vector to indicate reproductive animals (1= reproductive, 0 = productive)

if(SCALE== 2) REPRODUCTIVE <- c(1,0,0,0,0,0,0,0,0,0,0,0,0) else

REPRODUCTIVE <- c(0,0,0,0,0,0,0,0,0,0,0,0,0)

# Vector to indicate replacement animals (1= replacement, 0 = other)

REPLACEMENT <- c(0,1,0,0,0,0,0,0,0,0,0,0,0,0)

# Vector to indicate productive animals (1= productive, 0 = other)

PRODUCTIVE <- c(0,0,1,1,1,1,1,1,1,1,1,1,1,1)

# Auxilliary vector used later on in the code to obtain the right weather files

ORDER <- c(0,1,2,3,4,5,6,7,8,9,10)

# End of the section related to genetic parameters

###########################################################################################

# 1.3.2 Feed parameters #

###########################################################################################

# Feed parameters after often from Chilibroste et al. (1997) and Jarrige et al. (1986)

# Chilibroste P, Aguilar C and Garcia F 1997. Nutritional evaluation of diets. Simulation

# model of digestion and passage of nutrients through the rumen-reticulum. Animal Feed

# Science and Technology 68, 259-275.

# Jarrige R, Demarquilly C, Dulphy JP, Hoden A, Robelin J, Beranger C, Geay Y, Journet M,

# Malterre C, Micol D and Petit M 1986. The INRA fill unit system for predicting the

# voluntary intake of forage-based diets in ruminants - a review. Journal of Animal Science

# 63, 1737-1758.

# List of abbreviations:

# HIF = Heat Increment of feeding (MJ MJ-1 metabolisable energy, see Table S4 of the

# Supplementary Material)

# The following abbreviations correspond to the abbreviations used in Table S3 of the

# Supplementary Material:

# FU = Fill Units (-)

# SNSC = Soluble, Non-Structural Carbohydrates (g kg-1 DM)

# INSC = Insoluble, Non-Structural Carbohydrates (g kg-1 DM)

# DNDF = Digestible Neutral Detergent Fibre (g kg-1 DM)

# SCP = Soluble Crude Protein (g kg-1 DM)

# DCP = Digestible Crude Protein (g kg-1 DM)

# kdINSC = digestion rate Insoluble, Non-Structural Carbohydrates (% hr-1)

# kdNDF = digestion rate Neutral Detergent Fibre (% hr-1)

# kdDCP = digestion rate Digestible Crude Protein (% hr-1)

# kdPass = standard passage rate in the rumen (% hr-1)

# UNDF = Undegradable Neutral Detergent Fibre (g kg-1 DM)

# pef = physical effectiveness factor for Neutral Detergent Fibre (-)

# CP = crude protein (g kg DM-1)

# GE = gross energy (MJ kg DM-1)

####################################################################################################################

# The vectors and abbreviations for feed types given below correspond to Table S3 and S4

# of the Supplementary Material. For references to the parameters of feed types, see

# Tables S3 and S4

# SBM = soybean meal

# HIF FU SNSC INSC PNDF SCP PICP LEFT kdINSC kdPNDF kdPICP kdPASS UNDF NDF peNDF CP GE

# 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

BARLEY <- c(0.245, 0.573, 389, 214, 156.00, 34.50, 82.80, 116.70, 0.242, 0.145, 0.125, 0.040, 21.00, 0.210, 0.70, 110, 18.4)

CONCENTRATE <- c(0.249, 0.619, 262, 175, 243.10, 72.80, 87.36, 161.74, 0.150, 0.060, 0.100, 0.040, 42.90, 0.286, 0.70, 182, 18.5)

HAY <- c(0.318, 1.120, 100, 150, 345.80, 48.16, 74.30, 281.74, 0.300, 0.040, 0.085, 0.035, 148.20, 0.494, 1.00, 172, 18.5)

HAYPOOR <- c(0.420, 1.370, 73, 73, 462.00, 20.30,149.10, 347.90, 0.300, 0.040, 0.085, 0.035, 198.00, 0.660, 1.00, 70, 18.2)

GRASSSPRING <- c(0.304, 0.960, 130, 30, 360.00, 66.25, 97.40, 361.30, 0.300, 0.040, 0.085, 0.035, 120.00, 0.400, 0.40, 265, 18.6)

GRASSSUMMER <- c(0.356, 1.120, 100, 60, 376.00, 49.50, 76.50, 385.00, 0.300, 0.040, 0.085, 0.035, 141.00, 0.470, 0.50, 180, 18.4)

GRASSSUMMERDRY <- c(0.447, 1.280, 50, 60, 409.50, 23.00, 69.00, 411.50, 0.300, 0.040, 0.085, 0.035, 175.50, 0.585, 1.00, 115, 18.1)

MAIZE <- c(0.237, 0.438, 202, 532, 101.70, 20.10, 86.56, 57.64, 0.040, 0.051, 0.035, 0.050, 11.30, 0.113, 0.40, 134, 17.0)

MOLASSES <- c(0.050, 0.200, 828, 0, 0, 3.8, 0.2, 0, 0, 0, 0.125, 0.040, 0, 0, 0, 4, 17.0)

SBM <- c(0.242, 0.526, 107, 0, 138.60, 202.80,243.40, 232.00, 0.242, 0.145, 0.125, 0.040, 0.00, 0.210, 0.40, 507, 19.7)

STRAWCER <- c(0.557, 1.800, 14, 78, 401.00, 10.00, 5.00, 370.00, 0.300, 0.040, 0.085, 0.035, 0.00, 0.210, 1.00, 40, 18.3)

WHEAT <- c(0.234, 0.475, 475, 212, 80.00, 39.90, 69.80, 0.0, 0.182, 0.150, 0.080, 0.040, 34.20, 0.114, 0.70, 133, 18.2)

MAIZESILAGE <- c(0.289, 1.000, 100, 351, 239.00, 54.94, 23.00, 483.06, 0.250, 0.040, 0.040, 0.030, 239.00, 0.478, 0.93, 82, 18.5)

PASTURE <- c(0.323, 1.120, 100, 60, 376.00, 49.50, 76.50, 385.00, 0.300, 0.040, 0.085, 0.035, 141.00, 0.470, 0.50, 180, 18.4)

PASTURE <- c(0.323, 1.195, 100, 60, 376.00, 49.50, 76.50, 385.00, 0.300, 0.040, 0.085, 0.035, 141.00, 0.470, 0.50, 180, 18.4)

PASTURE1 <- c(0.358, 1.12, 50, 60, 551.00, 23.00, 69.00, 411.50, 0.300, 0.040, 0.085, 0.035, 175.50, 0.585, 1.00, 115, 18.1)

MIX <- (0.69\*SBM+0.31\*HAY)/1 # Model users can specify a mix of specific feed types. This

# indicates a mix between 69% soybean meal and 31% good

# quality hay.

####################################################################################################################

# Feed quality and available feed quantity (limiting factors for growth of beef cattle)

# Feed type

F1 <- matrix(nrow=length(DOY), ncol=length(BARLEY)) # Creates matrices for the types of

# feed types fed each day

F2 <- matrix(nrow=length(DOY), ncol=length(BARLEY))

F3 <- matrix(nrow=length(DOY), ncol=length(BARLEY))

FEED1 <- matrix(nrow=length(DOY), ncol=length(BARLEY))

FEED2 <- matrix(nrow=length(DOY), ncol=length(BARLEY))

FEED3 <- matrix(nrow=length(DOY), ncol=length(BARLEY))

FEED4 <- HAY # The fourth feed type is fixed, and cannot vary over time. The first three

# feed types can vary over time.

FEED1QNTY <- NULL # Creates matrix for the available feed quantity per day for feed 1

FEED2QNTY <- NULL # Creates matrix for the available feed quantity per day for feed 2

FEED3QNTY <- NULL # Creates matrix for the available feed quantity per day for feed 3

TIMESTEPS <- c(1:length(DOY)) # Counts the time steps (equal to number of days)

# Selection of feed types and feed quantities over simulation time if a specific diet

# (1-5) is chosen

for(i in 1:length(DOY)){

# Feed type 1

if(FEEDNR[z]==1) F1[i,] <- WHEAT

if(FEEDNR[z]==2) F1[i,] <- BARLEY

if(FEEDNR[z]==3) F1[i,] <- BARLEY

if(FEEDNR[z]==4) F1[i,] <- BARLEY

if(FEEDNR[z]==5) F1[i,] <- BARLEY

# Feed type 2

if(FEEDNR[z]==1) F2[i,] <- HAY

if(FEEDNR[z]==3) F2[i,] <- PASTURE1

if(TIMESTEPS[i] >=1 && TIMESTEPS[i] <=84 && FEEDNR[z]==2) F2[i,] <- HAY else

if(TIMESTEPS[i] >=85 && TIMESTEPS[i] <=344 && FEEDNR[z]==2)F2[i,] <- PASTURE1 else

if(TIMESTEPS[i] >=345 && TIMESTEPS[i] <=449 && FEEDNR[z]==2) F2[i,] <- HAY else

if(TIMESTEPS[i] >=450 && TIMESTEPS[i] <= 709 && FEEDNR[z]==2) F2[i,] <- PASTURE1 else

if(TIMESTEPS[i] >=710 && TIMESTEPS[i] <=814 && FEEDNR[z]==2) F2[i,] <- HAY else

if(TIMESTEPS[i] >=815 && TIMESTEPS[i] <=1074 && FEEDNR[z]==2)F2[i,] <- PASTURE1 else

if(TIMESTEPS[i] >=1075 && TIMESTEPS[i] <=1179 && FEEDNR[z]==2) F2[i,] <- HAY else

if(TIMESTEPS[i] >=1180 && TIMESTEPS[i] <= 1439 && FEEDNR[z]==2) F2[i,] <- PASTURE1 else

if(TIMESTEPS[i] >=1 && TIMESTEPS[i] <=84 && FEEDNR[z]==5) F2[i,] <- HAY else

if(TIMESTEPS[i] >=85 && TIMESTEPS[i] <=344 && FEEDNR[z]==5)F2[i,] <- PASTURE1 else

if(TIMESTEPS[i] >=345 && TIMESTEPS[i] <=449 && FEEDNR[z]==5) F2[i,] <- HAY else

if(TIMESTEPS[i] >=450 && TIMESTEPS[i] <= 709 && FEEDNR[z]==5) F2[i,] <- PASTURE1 else

if(TIMESTEPS[i] >=710 && TIMESTEPS[i] <=814 && FEEDNR[z]==5) F2[i,] <- HAY else

if(TIMESTEPS[i] >=815 && TIMESTEPS[i] <=1074 && FEEDNR[z]==5)F2[i,] <- PASTURE1 else

if(TIMESTEPS[i] >=1075 && TIMESTEPS[i] <=1179 && FEEDNR[z]==5) F2[i,] <- HAY else

if(TIMESTEPS[i] >=1180 && TIMESTEPS[i] <= 1439 && FEEDNR[z]==5) F2[i,] <- PASTURE1 else

F2[i,] <- HAY

# Feed type 3

F3[i,] <- HAY

if(TIMESTEPS[i] >=1 && TIMESTEPS[i] <=84 && FEEDNR[z]==4) F3[i,] <- HAY

if(TIMESTEPS[i] >=85 && TIMESTEPS[i] <=344 && FEEDNR[z]==4)F3[i,] <- PASTURE1

if(TIMESTEPS[i] >=345 && TIMESTEPS[i] <=449 && FEEDNR[z]==4) F3[i,] <- HAY

if(TIMESTEPS[i] >=450 && TIMESTEPS[i] <= 709 && FEEDNR[z]==4) F3[i,] <- PASTURE1

if(TIMESTEPS[i] >=710 && TIMESTEPS[i] <=814 && FEEDNR[z]==4) F3[i,] <- HAY

if(TIMESTEPS[i] >=815 && TIMESTEPS[i] <=1074 && FEEDNR[z]==4)F3[i,] <- PASTURE1

if(TIMESTEPS[i] >=1075 && TIMESTEPS[i] <=1179 && FEEDNR[z]==4) F3[i,] <- HAY

if(TIMESTEPS[i] >=1180 && TIMESTEPS[i] <= 1439 && FEEDNR[z]==4) F3[i,] <- PASTURE1

if(TIMESTEPS[i] >= 1439 && FEEDNR[z]==4) F3[i,] <- F3[i,] <- HAY

FEED1 <- F1

FEED2 <- F2

FEED3 <- F3

# Feed quantity available per animal (kg DM day-1) for feed type 1

FEED1QNTY[i] <- 20

if(FEEDNR[z]==4) FEED1QNTY[i] <- 1

if(FEEDNR[z]==5) FEED1QNTY[i] <- (2\*0.05)

# Feed quantity available per animal (kg DM day-1) for feed type 2

if(TIMESTEPS[i] <= 100) FEED2QNTY[i] <- ill.f1[z] else

if(TIMESTEPS[i] >=330 && TIMESTEPS[i] <=465) FEED2QNTY[i] <- ill.f1[z] else

FEED2QNTY[i] <- ill.f1[z]

# Feed quantity available per animal (kg DM day-1) for feed type 3

if(TIMESTEPS[i] <= 100) FEED3QNTY[i] <- ill.f2[z] else FEED3QNTY[i] <- ill.f2[z]

}

###########################################################################################

FEEDQNTYTOT <- FEED1QNTY + FEED2QNTY + FEED3QNTY # Feed quantity available per animal

# (kg DM day-1) for feed type 1-3

# Fractions of feed types in the diet over time (see column 'feed composition' of Table 1)

# Fraction of feed type 1 in the diet

if(FEEDNR[z] == 1) FEED1fr <- 0.65 else if(FEEDNR[z] == 2) FEED1fr <- 0.05 else

if(FEEDNR[z] == 3) FEED1fr <- 0.05 else if(FEEDNR[z] == 4) FEED1fr <- 0.65 else

if(FEEDNR[z] == 5) FEED1fr <- 0.05

# Fraction of feed type 2 in the diet

if(FEEDNR[z] == 1) FEED2fr <- 0.35 else if(FEEDNR[z] == 2) FEED2fr <- 0.95 else

if(FEEDNR[z] == 3) FEED2fr <- 0.95 else if(FEEDNR[z] == 4) FEED2fr <- 1.00 else

if(FEEDNR[z] == 5) FEED2fr <- 0.95

# Fraction of feed types 3 and 4 in the diet

FEED3fr <- 1.00

FEED4fr <- 1.00

###########################################################################################

# 1.3.3 General parameters #

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# General parameters used in physics and chemistry

# Numbers between brackets refer to parameter numbers in Table S5 of the Supplementary

# Material. For more background information on these parameters, see the subscripts of

# Table S5.

CtoK = 273.15 # [1] absolute zero temperature (K)

KtoR = 9/5 # [2] conversion degrees Kelvin to degrees Rankine

kJdaytoW = 1000/(3600\*24) # [3] conversion kJ day-1 to Watt

RUC = 0.00078 # [4] resistance conversion from s m-1 to W m-2 K-1

EMISS = 0.98 # [5] emissivity factor LWR (dimensionless)

GRAV = 9.81 # [6] gravitational constant (m s-2)

L = 2260 # [7] latent heat of vapour (kJ kg-1)

GAMMA = 66 # [8] psychrometric constant (Pa K-1)

TR0 = 524 # [9] reference temperature air (degrees Rankine)

REFLEgrass = 0.10 # [10] albedo vegetation (-)

REFLEconcr = 0.50 # albedo feedlot made of concrete (-)

Schmidt = 0.61 # [11] Schmidt number, dimensionless constant

# for calculation of the Grashof number

Rwater = 461.495 # [12] specific gas constant water vapour (J kg-1 K-1)

Cp = 1.005 # [13] specific heat of air (J kg-1 K-1)

P = 101325 # [14] standard air pressure at sea level (Pa)

MuSt = 1.827 \* 10^(-5) # [15] standard air viscosity (N s-1 m-2)

SIGMA = 5.67037 \* 10^-8 # [16] Stefan-Boltzmann constant (W m-2 K-4)

ST = 120 # [17] Sutherlands constant in standard air (degrees

# Rankine) for calculation air viscosity

Rdair = 287.058 # [18] universal gas constant (J kg-1 K-1)

CALTOJOULE = 4.184 # [19] conversion factor from calories to joules

NtoCP = 6.25 # [20] conversion from N to crude protein

GECARB = 17.4 # [21] gross energy carbohydrates, combustion value (MJ

# kg-1 DM)

GEFEED = 18.5 # [22] gross energy feed types in general, combustion

# value (MJ kg-1 DM)

GELIPID = 39.6 # [23] gross energy lipid, combustion value (MJ kg-1

# DM) (Emmans, 1994)

GEPROT = 23.8 # [24] gross energy protein, combustion value (MJ kg-1

# DM) (Emmans, 1994)

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# Parameters for cattle (not breed-specific)

# Numbers between brackets indicate parameter numbers as given in Table S6 of the

# Supplementary Material of Van der Linden et al.

CoatConst = 1.90 \* 10^(-5) \* SENSMAT[ 1,s] # [9] constant (m) (McGovern and Bruce,

# 2000)

ZC = 11000 \* SENSMAT[ 2,s] # [10] coat resistance (s m-2) (McGovern

# and Bruce, 2000)

TbodyC = 39 \* SENSMAT[ 3,s] # [8] body temperature animal (degrees

# Celsius) (McGovern and Bruce, 2000)

LASMIN = 10 \* SENSMAT[ 4,s] # [21] minimum latent heat release skin

# (W m-2) (Turnpenny et al., 2000a;

# Turnpenny et al., 2000b)

PHFEEDCAP = 123 \* SENSMAT[ 5,s] # [27] maximum feed intake of reference

# grass (g DM kg TBW-0.75) (Estimated

# from Jarrige et al., 1986)

RESPINCR = 7.64 \* SENSMAT[ 6,s] # [18] maximum increase in air exchange

# rate under heat stress (Calculated

# from McGovern and Bruce, 2000)

PROTFRACBONE = 0.23 \* SENSMAT[ 7,s] # [48] protein fraction in bone (Field

# et al., 1974)

PROTFRACMUSCLE = 0.21 \* SENSMAT[ 8,s] # [51] protein fraction in muscle

# (Consuleanu et al, 2008)

LIPFRACMUSCLE = 0.005 \* SENSMAT[ 9,s] # [47] lipid fraction in muscle (Warren

# et al., 2008)

PROTFRACFAT = 0.08 \* SENSMAT[10,s] # [49] protein fraction in fat tissue

# (Thonney, 2012)

LIPFRACFAT = 0.70 \* SENSMAT[11,s] # [46] lipid fraction in fat tissue

# (Thonney, 2012)

INCARC = 0.50 \* SENSMAT[12,s] # [35] fraction carcass at birth

# (estimate)

RUMENFRAC = 0.10 \* SENSMAT[13,s] # [52] fraction rumen in total body

# weight (estimate)

NEm = 311 \* SENSMAT[14,s] # [78] NE for maintenance (kJ NE kg

# EBW-0.75, for B. taurus cattle)

# (Ouellet et al, 1998)

NEpha = 70 \* SENSMAT[15,s] # [79] NE for physical activity (kJ NE

# kg EBW-0.75) (CSIRO, 2007)

BONEFRACMAX = 0.25 \* SENSMAT[16,s] # [64] maximum fraction bone in carcass

# (estimated from Berg and Butterfield,

# 1968)

LIPNONCMAX = 0.80 \* SENSMAT[17,s] # [65] maximum fraction lipid accretion

# in the non-carcass tissue (assumption,

# resembles fat tissue)

LIPNONCMIN = 0.15 \* SENSMAT[18,s] # [67] minimum fraction lipid accretion

# in the non-carcass tissue (assumption)

PROTEFF = 0.54 \* SENSMAT[19,s] # [76] NE efficiency of protein

# accretion (MSU, 2014)

LIPIDEFF = 0.74 \* SENSMAT[20,s] # [75] NE efficiency of lipid accretion

# (MSU, 2014)

DERMPL = 0.11 \* SENSMAT[21,s] # [39] dermal protein loss protein

# (g kg-0.75 EBW day-1) (CSIRO, 2007)

PROTNE = 2.0 / CALTOJOULE\* SENSMAT[22,s] # [88] protein requirement for NE

# (g MJ-1 NE) (CSIRO, 2007)

GestPer = 286 \* SENSMAT[23,s] # [53] gestation period (days)

# (Blanc and Agabriel, 2008)

GESTINTERVAL = 365 \* SENSMAT[24,s] # [66] minimum calving interval in days

WEANINGTIME = 210 \* SENSMAT[25,s] # [89] weaning time in days

# (Jenkins and Ferrell, 1992)

FtoConcW = 75/45 \* SENSMAT[26,s] # [37] conversion foetus weight to total

# concepta weight (Jarrige et al., 1986,

# p. 99)

FATFACTOR = 0.065 \* SENSMAT[27,s] # [45] factor determing fat accretion ()

RAINEXP = 0.50 \* SENSMAT[28,s] # [16] fraction animal area exposed to

# rain

FRACVEG = 0.50 \* SENSMAT[29,s] # [17] fraction of the animal facing the

# vegetation in free grazing systems

COMPFACT = 4 \* SENSMAT[30,s] # [44] factor indicating the magnitude

# in compensatory growth (dimensionless)

NEIEFFGEST = 0.766 \* SENSMAT[31,s] # [73] inefficiency of NE for gestation

# (1-efficiency) Calculated based on

# Jarrige (1989) and Rattray et al.

# (1974)

CPGEST = 4.322 \* SENSMAT[32,s] # [38] protein requirements for

# gestation (g protein MJ-1 NE)

MILKDIG = 0.95 \* SENSMAT[33,s] # [40] digestible fraction of milk,

# based on energy content of milk

NEEFFMILK = 0.85 \* SENSMAT[34,s] # [74] efficiency of conversion of NE to

# milk (energy basis)

PROTFRACMILK = 0.04 \* SENSMAT[35,s] # [50] fraction protein in milk

PROTEFFMILK = 0.68 \* SENSMAT[36,s] # [82] protein efficiency for milk

# production (CSIRO, 2007)

COMPFACTTIS = 1.20 \* SENSMAT[37,s] # [63] maximum multiplicative for

# compensatory growth (set at 120% of

# genetic potential)

FATTISCOMP = 0.80 \* SENSMAT[38,s] # [36] if fat tissue is lower than 80%

# of the potential, energy is allocated

# to the fat tissue for 'refill'

TTDIGINSC = 0.97 \* SENSMAT[39,s] # [31] fraction total tract

# digestibility of insoluble,

# non-structural carbohydrates

# (Moharrery et al, 2014)

DETOME = 0.82 \* SENSMAT[40,s] # [26] conversion from digestible

# energy (DE) to metabolisable energy

# (ME)

DISSEFF = 0.90 \* SENSMAT[41,s] # [41] efficiency of dissimilation of

# protein and lipid

RAINFRAC = 0.3 \* SENSMAT[91,s] # [22] 30% reduction in conductance due

# to rain (Mount and Brown, 1982)

BONEGROWTH1 = 0.6436 \* SENSMAT[68,s] # [33] bone growth parameter (kg)

BONEGROWTH2 = 0.262 \* SENSMAT[69,s] # [34] bone growth parameter (kg)

MUSCLEGROWTH1 = -2\*10^-5 \* SENSMAT[70,s] # [68] muscle growth parameter

MUSCLEGROWTH2 = 1.564 \* SENSMAT[71,s] # [69] muscle growth parameter

IMFGROWTH1 = 0.0001 \* SENSMAT[72,s] # [56] intramuscular fat growth

# parameter

IMFGROWTH2 = 0.01 \* SENSMAT[73,s] # [57] intramuscular fat growth

# parameter

IMFGROWTH3 = 0.04 \* SENSMAT[74,s] # [58] intramuscular fat growth

# parameter

PROTNONCM1 = -7.014\*(10^-3) \* SENSMAT[75,s] # [80] max. protein content non-carcass

PROTNONCM2 = 20.4 \* SENSMAT[76,s] # [81] max. protein content non-carcass

RESPDUR = 0.25 \* SENSMAT[77,s] # [23] fraction day maximum respiration

# is used

BODYAREA1 = 0.14 \* SENSMAT[78,s] # [4] parameter to calculate body area

# (m-2)

BODYAREA2 = 0.57 \* SENSMAT[79,s] # [5] parameter to calculate body area

# (m-2)

DIAMETER1 = 0.06 \* SENSMAT[80,s] # [6] parameter to calculate body

# diameter (m-2)

DIAMETER2 = 0.39 \* SENSMAT[81,s] # [7] parameter to calculate body

# diameter (m-2)

BASALRR1 = 73.8 \* SENSMAT[82,s] # [1] basal respiration rate (min-1)

BASALRR2 = -0.286 \* SENSMAT[83,s] # [2] basal respiration rate

BASALTV = 0.0117 \* SENSMAT[84,s] # [3] basal tidal volume (L min-1)

TEXHALED1 = 17 \* SENSMAT[85,s] # [12] exhaled temperature (degrees

# Celsius)

TEXHALED2 = 0.3 \* SENSMAT[86,s] # [13] exhaled temperature

TEXHALED3 = 0.01611 \* SENSMAT[87,s] # [14] exhaled temperature

TEXHALED4 = 0.0387 \* SENSMAT[88,s] # [15] exhaled temperature

MINCCS1 = 0.03 \* SENSMAT[89,s] # [19] min. conductance core-skin (W

# m-2 K-1)

MINCCS2 = 0.33 \* SENSMAT[90,s] # [20] min. conductance core-skin

# (kg-1 total body weight)

RAINEVAP1 = 0.15 \* SENSMAT[92,s] # [11] evaporation rain from coat

GEMILK1 = 5.5109 \* SENSMAT[94,s] # [54] gross energy milk (kJ L-1)

GEMILK2 = 2589 \* SENSMAT[95,s] # [55] gross energy milk (kJ L-1)

LIPBONE1 = 0.075 \* SENSMAT[96,s] # [59] lipid fraction bone

LIPBONE2 = 3.0496 \* SENSMAT[97,s] # [60] lipid fraction bone

LIPBONE3 = 3.3268 \* SENSMAT[98,s] # [61] lipid fraction bone

LIPNONC1 = 4.7915\*10^-7 \* SENSMAT[99,s] # [62] lipid fraction non-carcass

LIPNONC2 = 0.00010757 \* SENSMAT[100,s] # [62] lipid fraction non-carcass

LIPNONC3 = 0.105717 \* SENSMAT[101,s] # [62] lipid fraction non-carcass

LIPNONC4 = 2.1723 \* SENSMAT[102,s] # [62] lipid fraction non-carcass

PROTNONC1 = 8.7492\*10^-10 \* SENSMAT[103,s] # [83] protein fraction non-carcass

PROTNONC2 = 9.0732\*10^-7 \* SENSMAT[104,s] # [84] protein fraction non-carcass

PROTNONC3 = 0.00033117 \* SENSMAT[105,s] # [85] protein fraction non-carcass

PROTNONC4 = 0.061756 \* SENSMAT[106,s] # [86] protein fraction non-carcass

PROTNONC5 = 22.26 \* SENSMAT[107,s] # [87] protein fraction non-carcass

RUMENDEV1 = 0.007246 \* SENSMAT[108,s] # [29] parameter rumen development

RUMENDEV2 = 0.101449 \* SENSMAT[109,s] # [30] parameter rumen development

NDFDIGEST = 0.9 \* SENSMAT[110,s] # [32] total tract DNDF digestibility

NDFPASS = 0.125 \* SENSMAT[111,s] # [28] passage rate DNDF

LUCAS1 = 0.9 \* SENSMAT[112,s] # [24] slope Lucas equation

LUCAS2 = 32 \* SENSMAT[113,s] # [25] intercept Lucas equation

# (g kg-1 DM)

ENNONC1 = 0.60 \* SENSMAT[114,s] # [42] energy partitioning non-carcass

ENNONC2 = 0.03 \* SENSMAT[115,s] # [43] energy partitioning non-carcass

NRECYCL1 = 121.7 \* SENSMAT[116,s] # [70] N recycling

NRECYCL2 = 12.01 \* SENSMAT[117,s] # [71] N recycling

NRECYCL3 = 0.3235 \* SENSMAT[118,s] # [72] N recycling

# Gross energy content fat tissue (MJ kg-1)

GEFATTIS = GEPROT \* PROTFRACFAT + GELIPID \* LIPFRACFAT

# Gross energy content muscle tissue (MJ kg-1)

GEMUSCLETIS = GEPROT \* PROTFRACMUSCLE + GELIPID \* LIPFRACMUSCLE

# Passage reduction factors for different classes of rumen fill (Chilibroste et al, 1997)

PASSRED <- c(1,0.85,0.65,0.55)

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# 1.4 Specification of variables #

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# 1.4.1 Specification of variables for the feed intake and digestion sub-model #

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# Available feed quantity for feed type 1 (kg DM per animal per day)

FEED1QNTY <- matrix(nrow=length(DOY), ncol = jmax, byrow = F, rep(FEED1QNTY,jmax))

FEED1QNTY <- FEED1QNTY[1:imax,]

# Available feed quantity for feed type 2 (kg DM per animal per day)

FEED2QNTY <- matrix(nrow=length(DOY), ncol = jmax, byrow = F, rep(FEED2QNTY,jmax))

FEED2QNTY <- FEED2QNTY[1:imax,]

# Available feed quantity for feed type 3 (kg DM per animal per day)

FEED3QNTY <- matrix(nrow=length(DOY), ncol = jmax, byrow = F, rep(FEED3QNTY,jmax))

FEED3QNTY <- FEED3QNTY[1:imax,]

# Available feed quantity for feed type 4 (kg DM per animal per day)

FEED4QNTY <- c(rep(rep( 0.0,imax),jmax))

FEED1QNTY <- matrix(nrow=imax, ncol=jmax, FEED1QNTY)

FEED2QNTY <- matrix(nrow=imax, ncol=jmax, FEED2QNTY)

FEED3QNTY <- matrix(nrow=imax, ncol=jmax, FEED3QNTY)

FEED4QNTY <- matrix(nrow=imax, ncol=jmax, FEED4QNTY)

FEEDQNTY <- FEED1QNTY + FEED2QNTY + FEED3QNTY + FEED4QNTY

FRACFEED1 <- matrix(nrow=imax, ncol=jmax)

FRACFEED2 <- matrix(nrow=imax, ncol=jmax)

FRACFEED3 <- matrix(nrow=imax, ncol=jmax)

FRACFEED4 <- matrix(nrow=imax, ncol=jmax)

FEED1QNTYA <- matrix(nrow=imax, ncol=jmax)

FEED2QNTYA <- matrix(nrow=imax, ncol=jmax)

FEED3QNTYA <- matrix(nrow=imax, ncol=jmax)

FEED4QNTYA <- matrix(nrow=imax, ncol=jmax)

PASSDIFF <- matrix(nrow=imax, ncol=jmax)

PENDF <- matrix(nrow=imax, ncol=jmax)

Digestfracfeed <- matrix(nrow=imax, ncol=jmax)

INSC <- matrix(nrow=imax, ncol=jmax)

INSCTOTAL <- matrix(nrow=imax, ncol=jmax)

INSCDIG <- matrix(nrow=imax, ncol=jmax)

INSCINT <- matrix(nrow=imax, ncol=jmax)

INSCINTDIG <- matrix(nrow=imax, ncol=jmax)

NDF <- matrix(nrow=imax, ncol=jmax)

NDFTOTAL <- matrix(nrow=imax, ncol=jmax)

NDFDIG <- matrix(nrow=imax, ncol=jmax)

NDFINT <- matrix(nrow=imax, ncol=jmax)

NDFINTDIG <- matrix(nrow=imax, ncol=jmax)

NDFINTDIGTOT <- matrix(nrow=imax, ncol=jmax)

PICP <- matrix(nrow=imax, ncol=jmax)

PROTTOTAL <- matrix(nrow=imax, ncol=jmax)

PROTINT <- matrix(nrow=imax, ncol=jmax)

PROTUPT <- matrix(nrow=imax, ncol=jmax)

PROTEXCR <- matrix(nrow=imax, ncol=jmax)

PROTDIGRU <- matrix(nrow=imax, ncol=jmax)

PROTDIGWT <- matrix(nrow=imax, ncol=jmax)

PROTBAL <- matrix(nrow=imax, ncol=jmax)

PROTREDFACT <- matrix(nrow=imax, ncol=jmax)

DIGFRAC <- matrix(nrow=imax, ncol=jmax)

CHEXCR <- matrix(nrow=imax, ncol=jmax)

EXCRFRAC <- matrix(nrow=imax, ncol=jmax)

GEEXCR <- matrix(nrow=imax, ncol=jmax)

GEUPTAKE <- matrix(nrow=imax, ncol=jmax)

MEUPTAKE <- matrix(nrow=imax, ncol=jmax)

Q <- matrix(nrow=imax, ncol=jmax)

PHFEEDINT = matrix(nrow=imax, ncol=jmax)

PHFEEDINTKG = matrix(nrow=imax, ncol=jmax)

PASSAGE = matrix(nrow=imax, ncol=jmax)

PASSAGE1 = matrix(nrow=imax, ncol=jmax)

FUFEED1 = matrix(nrow=imax, ncol=jmax)

FUFEED2 = matrix(nrow=imax, ncol=jmax)

FUFEED3 = matrix(nrow=imax, ncol=jmax)

FUFEED4 = matrix(nrow=imax, ncol=jmax)

AVGDIGFRAC = matrix(nrow=imax, ncol=jmax)

MEDAILYMAX = matrix(nrow=imax, ncol=jmax)

MEDIGLIMGR = matrix(nrow=imax, ncol=jmax)

FEEDINTAKE = matrix(nrow=imax, ncol=jmax)

FILLGIT = matrix(nrow=imax, ncol=jmax)

###########################################################################################

# 1.4.2 Specification of variables for the thermoregulation sub-model #

###########################################################################################

# 1. Respiration

TBW = matrix(nrow=imax+1, ncol=jmax)

AREA = matrix(nrow=imax, ncol=jmax)

DIAMETER = matrix(nrow=imax, ncol=jmax)

LENGTH = matrix(nrow=imax, ncol=jmax)

brr = matrix(nrow=imax, ncol=jmax)

btv = matrix(nrow=imax, ncol=jmax)

Vtb = matrix(nrow=imax, ncol=jmax)

brv = matrix(nrow=imax, ncol=jmax)

irv = matrix(nrow=imax, ncol=jmax)

TAVGC = matrix(nrow=imax, ncol=jmax)

TAVGK = matrix(nrow=imax, ncol=jmax)

VPSATAIR = matrix(nrow=imax, ncol=jmax)

VPAIRTOT = matrix(nrow=imax, ncol=jmax)

RHAIR = matrix(nrow=imax, ncol=jmax)

RHOVP = matrix(nrow=imax, ncol=jmax)

RHODAIR = matrix(nrow=imax, ncol=jmax)

RHOAIR = matrix(nrow=imax, ncol=jmax)

CHIAIR = matrix(nrow=imax, ncol=jmax)

VISCAIR = matrix(nrow=imax, ncol=jmax)

Texh = matrix(nrow=imax, ncol=jmax)

VPSATAIROUT = matrix(nrow=imax, ncol=jmax)

RHOVPOUT = matrix(nrow=imax, ncol=jmax)

RHODAIROUT = matrix(nrow=imax, ncol=jmax)

RHOAIROUT = matrix(nrow=imax, ncol=jmax)

CHIAIROUT = matrix(nrow=imax, ncol=jmax)

AIREXCH = matrix(nrow=imax, ncol=jmax)

LHEATRESP = matrix(nrow=imax, ncol=jmax)

CHEATRESP = matrix(nrow=imax, ncol=jmax)

TGRESP = matrix(nrow=imax, ncol=jmax)

TNRESP = matrix(nrow=imax, ncol=jmax)

TNRESPH = matrix(nrow=imax, ncol=jmax)

NERESP = matrix(nrow=imax, ncol=jmax)

NERESPWM = matrix(nrow=imax, ncol=jmax)

NERESPC = matrix(nrow=imax, ncol=jmax)

MetheatSKIN = matrix(nrow=imax, ncol=jmax)

TskinC = matrix(nrow=imax, ncol=jmax)

TskinCH = matrix(nrow=imax, ncol=jmax)

CBSMIN = matrix(nrow=imax, ncol=jmax)

CONDBS = matrix(nrow=imax, ncol=jmax)

# 2. Latent heat release from the skin

DLC = matrix(nrow=imax, ncol=jmax)

DIFFC = matrix(nrow=imax, ncol=jmax)

RV = matrix(nrow=imax, ncol=jmax)

VPSKINTOT = matrix(nrow=imax, ncol=jmax)

LASMAXENV = matrix(nrow=imax, ncol=jmax)

LASMAXPHYS = matrix(nrow=imax, ncol=jmax)

LASMAXCORR = matrix(nrow=imax, ncol=jmax)

ACTSW = matrix(nrow=imax, ncol=jmax)

ACTSWH = matrix(nrow=imax, ncol=jmax)

CSC = matrix(nrow=imax, ncol=jmax)

MetheatCOAT = matrix(nrow=imax, ncol=jmax)

TcoatC = matrix(nrow=imax, ncol=jmax)

TcoatCH = matrix(nrow=imax, ncol=jmax)

TcoatK = matrix(nrow=imax, ncol=jmax)

# 3.LWR heat balance of the coat

LWRSKY = matrix(nrow=imax, ncol=jmax)

LWRENV = matrix(nrow=imax, ncol=jmax)

LB = matrix(nrow=imax, ncol=jmax)

LWRCOAT = matrix(nrow=imax, ncol=jmax)

LWRCOATH = matrix(nrow=imax, ncol=jmax)

# 4.Convective heat losses from the coat

TAVGR = matrix(nrow=imax, ncol=jmax)

Ea = matrix(nrow=imax, ncol=jmax)

Ec = matrix(nrow=imax, ncol=jmax)

GRASHOF = matrix(nrow=imax, ncol=jmax)

WINDSP = matrix(nrow=imax, ncol=jmax)

REYNOLDS = matrix(nrow=imax, ncol=jmax)

ReH = matrix(nrow=imax, ncol=jmax)

ReL = matrix(nrow=imax, ncol=jmax)

NUSSELTH = matrix(nrow=imax, ncol=jmax)

NUSSELTL = matrix(nrow=imax, ncol=jmax)

NUSSELT = matrix(nrow=imax, ncol=jmax)

NUSSELTM = matrix(nrow=imax, ncol=jmax)

ka = matrix(nrow=imax, ncol=jmax)

CONVCOAT = matrix(nrow=imax, ncol=jmax)

CONVCOATH = matrix(nrow=imax, ncol=jmax)

# 5. Incoming SWR (solar radiation) to coat

SAAC = matrix(nrow=imax, ncol=jmax)

SWRS = matrix(nrow=imax, ncol=jmax)

SWRC = matrix(nrow=imax, ncol=jmax)

ISWRC = matrix(nrow=imax, ncol=jmax)

REFLE = NULL

SWR = matrix(nrow=imax, ncol=jmax)

RAINEVAP = matrix(nrow=imax, ncol=jmax)

# Synthesis and optimization with repeat {} function

MetheatBAL = matrix(nrow=imax, ncol=jmax)

Metheatopt = matrix(nrow=imax, ncol=jmax)

METABFEED0 = matrix(rep(100,imax\*jmax),nrow=imax, ncol=jmax)

###########################################################################################

# 1.4.3 Specification of variables for energy and protein utilisation sub-model #

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# Synthesis and optimisation

EX = matrix(nrow=imax, ncol=jmax)

# Weight and derivative body tissues

ADGHIGH = matrix(nrow=imax+1, ncol=jmax)

ADGHIGH[1,1:jmax] <- 0

TBWCHECK = matrix(nrow=imax+1, ncol=jmax)

CARCW = matrix(nrow=imax+1, ncol=jmax)

BONETIS = matrix(nrow=imax+1, ncol=jmax)

MUSCLETIS = matrix(nrow=imax+1, ncol=jmax)

INTRAMFTIS = matrix(nrow=imax+1, ncol=jmax)

MISCFATTIS = matrix(nrow=imax+1, ncol=jmax)

NONCARCTIS = matrix(nrow=imax+1, ncol=jmax)

RUMEN = matrix(nrow=imax+1, ncol=jmax)

DERBONE = matrix(nrow=imax+1, ncol=jmax)

DERMUSCLE = matrix(nrow=imax+1, ncol=jmax)

DERINTRAMF = matrix(nrow=imax+1, ncol=jmax)

DERMISCFAT = matrix(nrow=imax+1, ncol=jmax)

DERNONC = matrix(nrow=imax+1, ncol=jmax)

DERRUMEN = matrix(nrow=imax+1, ncol=jmax)

DERTOTAL = matrix(nrow=imax+1, ncol=jmax)

# Lipid and protein concentrations in body tissues

LIPIDFRACBONE = matrix(nrow=imax+1, ncol=jmax)

LIPIDFRACBONEBF = matrix(nrow=imax+1, ncol=jmax)

LIPIDFRACNONC = matrix(nrow=imax+1, ncol=jmax)

LIPIDFRACNONCBF = matrix(nrow=imax+1, ncol=jmax)

PROTFRACNONC = matrix(nrow=imax+1, ncol=jmax)

PROTFRACNONCBF = matrix(nrow=imax+1, ncol=jmax)

ENFEEDGROWTH = matrix(nrow=imax+1, ncol=jmax)

ENFEEDGROWTHQ = matrix(nrow=imax+1, ncol=jmax)

# Bone carcass

LIPIDBONE = matrix(nrow=imax+1, ncol=jmax)

PROTBONE = matrix(nrow=imax+1, ncol=jmax)

ENGRBONE = matrix(nrow=imax+1, ncol=jmax)

# Muscle carcass

LIPIDMUSCLE = matrix(nrow=imax+1, ncol=jmax)

PROTMUSCLE = matrix(nrow=imax+1, ncol=jmax)

ENGRMUSCLE = matrix(nrow=imax+1, ncol=jmax)

# Intramuscular fat

LIPIDIMF = matrix(nrow=imax+1, ncol=jmax)

PROTIMF = matrix(nrow=imax+1, ncol=jmax)

ENGRIMF = matrix(nrow=imax+1, ncol=jmax)

# Subcutaneous and intermuscular fat

LIPIDFAT = matrix(nrow=imax+1, ncol=jmax)

PROTFAT = matrix(nrow=imax+1, ncol=jmax)

ENGRFAT = matrix(nrow=imax+1, ncol=jmax)

# Non carcass tissue

LIPIDNONC = matrix(nrow=imax+1, ncol=jmax)

PROTNONC = matrix(nrow=imax+1, ncol=jmax)

ENGRNONC = matrix(nrow=imax+1, ncol=jmax)

# Growth influenced by defining and limiting biophyscial factors

ENGRNONCBF = matrix(nrow=imax+1, ncol=jmax)

ENGRBONEBF = matrix(nrow=imax+1, ncol=jmax)

ENGRIMFBF = matrix(nrow=imax+1, ncol=jmax)

ENGRMUSCLEBF = matrix(nrow=imax+1, ncol=jmax)

ENGRFATBF = matrix(nrow=imax+1, ncol=jmax)

ENGRTOTAL = matrix(nrow=imax+1, ncol=jmax)

ENGRTOTALHIGH = matrix(nrow=imax+1, ncol=jmax)

ENGRTOTALHIGH[1,1:jmax] <- 0

ENGRTOTALHIGH1 = matrix(nrow=imax+1, ncol=jmax)

ENGRTOTALHIGH1[1,1:jmax] <- 0

REL = matrix(nrow=imax+1, ncol=jmax)

REL[1,1:jmax] <- 0

ENGRTOTALORIG = matrix(nrow=imax+1, ncol=jmax)

FRENGRNONCBF = matrix(nrow=imax+1, ncol=jmax)

FRENGRBONEBF = matrix(nrow=imax+1, ncol=jmax)

FRENGRIMFBF = matrix(nrow=imax+1, ncol=jmax)

FRENGRMUSCLEBF = matrix(nrow=imax+1, ncol=jmax)

FRENGRFATBF = matrix(nrow=imax+1, ncol=jmax)

FRENGRTOTAL = matrix(nrow=imax+1, ncol=jmax)

BONETISBF = matrix(nrow=imax+1, ncol=jmax)

MUSCLETISBF = matrix(nrow=imax+1, ncol=jmax)

INTRAMFTISBF = matrix(nrow=imax+1, ncol=jmax)

MISCFATTISBF = matrix(nrow=imax+1, ncol=jmax)

NONCARCTISBF = matrix(nrow=imax+1, ncol=jmax)

TBWBF = matrix(nrow=imax+1, ncol=jmax)

EBWBFMET = matrix(nrow=imax+1, ncol=jmax)

MISCFATFRAC = matrix(nrow=imax+1, ncol=jmax)

LIPIDBONEBF = matrix(nrow=imax+1, ncol=jmax)

LIPIDNONCBF = matrix(nrow=imax+1, ncol=jmax)

PROTNONCBF = matrix(nrow=imax+1, ncol=jmax)

LIPIDMUSCLEBF = matrix(nrow=imax+1, ncol=jmax)

LIPIDIMFBF = matrix(nrow=imax+1, ncol=jmax)

LIPIDFATBF = matrix(nrow=imax+1, ncol=jmax)

LIPIDTOTW = matrix(nrow=imax+1, ncol=jmax)

LIPIDFRACCARC = matrix(nrow=imax+1, ncol=jmax)

ENCONTENTNONCBF = matrix(nrow=imax+1, ncol=jmax)

# Maintenance

NEMAINT = matrix(nrow=imax, ncol=jmax)

NEMAINTWM = matrix(nrow=imax, ncol=jmax)

PROTDERML = matrix(nrow=imax, ncol=jmax)

PROTMAINT = matrix(nrow=imax, ncol=jmax)

PROTRESP = matrix(nrow=imax, ncol=jmax)

# Physical activity

NEPHYSACT = matrix(nrow=imax, ncol=jmax)

NEPHYSACTWM = matrix(nrow=imax, ncol=jmax)

PROTPHACT = matrix(nrow=imax, ncol=jmax)

# Gestation

CALFTBW = matrix(nrow=imax+1, ncol=jmax)

CALFNR = matrix(nrow=imax+1, ncol=jmax)

BIRTHW1 = matrix(nrow=imax, ncol=jmax)

GEST1 = matrix(nrow=imax, ncol=jmax)

GEST2 = matrix(nrow=imax, ncol=jmax)

GEST3 = matrix(nrow=imax, ncol=jmax)

GEST4 = matrix(nrow=imax, ncol=jmax)

GEST5 = matrix(nrow=imax, ncol=jmax)

GEST6 = matrix(nrow=imax+1, ncol=jmax)

GEST = matrix(nrow=imax, ncol=jmax)

GESTDAY = matrix(nrow=imax+1, ncol=jmax)

NEREQGEST = matrix(nrow=imax, ncol=jmax)

NEREQGESTADD = matrix(nrow=imax+1, ncol=jmax)

NEREQGESTTOT = matrix(nrow=imax, ncol=jmax)

HEATGEST = matrix(nrow=imax, ncol=jmax)

PROTGESTG = matrix(nrow=imax, ncol=jmax)

TBWADD = matrix(nrow=imax+1, ncol=jmax)

# Milk production

MILKDAYST = matrix(nrow=imax, ncol=jmax)

MILKDAY = matrix(nrow=imax+1, ncol=jmax)

MILKWEEK = matrix(nrow=imax+1, ncol=jmax)

ADDMILK1 = matrix(nrow=imax, ncol=jmax)

ADDMILK2 = matrix(nrow=imax, ncol=jmax)

MAXMILKPROD = matrix(nrow=imax, ncol=jmax)

GEMILK = matrix(nrow=imax, ncol=jmax)

GEMILKTOT = matrix(nrow=imax, ncol=jmax)

MEMILKCALF = matrix(nrow=imax, ncol=jmax)

MEMILKCALFINIT = matrix(nrow=imax, ncol=jmax)

NEMILKCOW = matrix(nrow=imax, ncol=jmax)

CALFLIVENR = matrix(nrow=imax, ncol=jmax)

CALFWEANNR = matrix(nrow=imax, ncol=jmax)

MILKPRODBF = matrix(nrow=imax, ncol=jmax)

HEATMILK = matrix(nrow=imax, ncol=jmax)

NETMILKEN = matrix(nrow=imax+1, ncol=jmax)

PROTMILK = matrix(nrow=imax, ncol=jmax)

PROTMILKG = matrix(nrow=imax, ncol=jmax)

# ME total

MEREQTOTAL = matrix(nrow=imax, ncol=jmax)

MEREQTOTAL2 = matrix(nrow=imax, ncol=jmax)

NETMILKEN = matrix(nrow=imax, ncol=jmax)

# Cold stress

Metheatcold = matrix(rep(NA,imax\*jmax), nrow=imax, ncol=jmax)

METABSTARTCOLD = matrix(rep(100,imax\*jmax),nrow=imax, ncol=jmax)

TOTHEAT = matrix(nrow=imax, ncol=jmax)

FATBURN = matrix(nrow=imax, ncol=jmax)

REDTIS2 = matrix(nrow=imax, ncol=jmax)

REDTIS3 = matrix(nrow=imax, ncol=jmax)

MAINTFRAC = matrix(nrow=imax, ncol=jmax)

FATFRACCARC = matrix(nrow=imax, ncol=jmax)

###########################################################################################

# 1.4.4 Variables for integration of sub-models #

###########################################################################################

COMPGROWTH = matrix(nrow=imax+1, ncol=jmax)

COMPGROWTH1 = matrix(nrow=imax+1, ncol=jmax)

COMPGROWTH2 = matrix(nrow=imax+1, ncol=jmax)

COMPGROWTH3 = matrix(nrow=imax+1, ncol=jmax)

COMPGROWTH4 = matrix(nrow=imax+1, ncol=jmax)

COMPGROWTH5 = matrix(nrow=imax+1, ncol=jmax)

ENGRTOTALCOMP = matrix(nrow=imax+1, ncol=jmax)

HEATBONEACT = matrix(nrow=imax+1, ncol=jmax)

HEATMUSCLEACT = matrix(nrow=imax+1, ncol=jmax)

HEATIMFACT = matrix(nrow=imax+1, ncol=jmax)

HEATMISCFATACT = matrix(nrow=imax+1, ncol=jmax)

HEATNONCACT = matrix(nrow=imax+1, ncol=jmax)

HEATTOTALACT = matrix(nrow=imax+1, ncol=jmax)

ENBONEACT = matrix(nrow=imax+1, ncol=jmax)

ENMUSCLEACT = matrix(nrow=imax+1, ncol=jmax)

ENIMFACT = matrix(nrow=imax+1, ncol=jmax)

ENMISCFATACT = matrix(nrow=imax+1, ncol=jmax)

ENNONCACT = matrix(nrow=imax+1, ncol=jmax)

ENTOTALACT = matrix(nrow=imax+1, ncol=jmax)

PROTBONEACT = matrix(nrow=imax+1, ncol=jmax)

PROTMUSCLEACT = matrix(nrow=imax+1, ncol=jmax)

PROTIMFACT = matrix(nrow=imax+1, ncol=jmax)

PROTMISCFATACT = matrix(nrow=imax+1, ncol=jmax)

PROTNONCBF1 = matrix(nrow=imax+1, ncol=jmax)

PROTTOTALACT = matrix(nrow=imax+1, ncol=jmax)

PROTGROSS = matrix(nrow=imax+1, ncol=jmax)

UREABL = matrix(nrow=imax+1, ncol=jmax)

NRECYCLPT = matrix(nrow=imax+1, ncol=jmax)

PROTNETT = matrix(nrow=imax+1, ncol=jmax)

PROTACCR = matrix(nrow=imax+1, ncol=jmax)

HEATCLIMGEN = matrix(nrow=imax+1, ncol=jmax)

DIFFEN = matrix(nrow=imax+1, ncol=jmax)

HEATIFEEDMAINT = matrix(nrow=imax, ncol=jmax)

HEATIFEEDMAINTWM = matrix(nrow=imax, ncol=jmax)

HEATIFEEDGROWTH = matrix(nrow=imax, ncol=jmax)

HEATIFEEDGROWTHWM = matrix(nrow=imax, ncol=jmax)

HEATIFEEDGROWTHC = matrix(nrow=imax, ncol=jmax)

HEATIFEEDGROWTHCWM = matrix(nrow=imax, ncol=jmax)

REDMAINT = matrix(nrow=imax, ncol=jmax)

REDMAINT2 = matrix(nrow=imax, ncol=jmax)

REDMAINT3 = matrix(nrow=imax, ncol=jmax)

REDTIS = matrix(nrow=imax, ncol=jmax)

REDTISPROT = matrix(nrow=imax, ncol=jmax)

CHECK = matrix(nrow=imax, ncol=jmax)

REDHP = matrix(nrow=imax, ncol=jmax)

###########################################################################################

# 1.4.5 Variables for herd dynamics and output #

###########################################################################################

TIME = matrix(nrow=imax, ncol=jmax)

TIME2 = matrix(nrow=imax+1, ncol=jmax)

TIMEYEAR = matrix(nrow=imax, ncol=jmax)

TIMEYEAR2 = matrix(nrow=imax+1, ncol=jmax)

BIRTHDAYCALF1 = 1 # Initial values for birthdays calves (days)

BIRTHDAYCALF2 = 1 # Calculated as days after birth reproductive animal

BIRTHDAYCALF3 = 1 # Values are recalculated

BIRTHDAYCALF4 = 1

BIRTHDAYCALF5 = 1

BIRTHDAYCALF6 = 1

BIRTHDAYCALF7 = 1

BIRTHDAYCALF8 = 1

BIRTHDAYCALF9 = 1

BIRTHDAY = NULL

WNDAY = NULL

# Modelling calves and cow parity

PARITY1 = matrix(nrow=imax, ncol=jmax) # Cow has been or is in the first parity

PARITY2 = matrix(nrow=imax, ncol=jmax) # Cow has been or is in the second parity

PARITY3 = matrix(nrow=imax, ncol=jmax) # Cow has been or is in the third parity

PARITY4 = matrix(nrow=imax, ncol=jmax) # Cow has been or is in the fourth parity

PARITY5 = matrix(nrow=imax, ncol=jmax) # Cow has been or is in the fifth parity

PARITY6 = matrix(nrow=imax, ncol=jmax) # Cow has been or is in the sixth parity

PARITY7 = matrix(nrow=imax, ncol=jmax) # Cow has been or is in the seventh parity

PARITY8 = matrix(nrow=imax, ncol=jmax) # Cow has been or is in the eighth parity

PARITY9 = matrix(nrow=imax, ncol=jmax) # Cow has been or is in the nineth parity

# Herd dynamics

BEEFPROD = matrix(nrow=imax+1, ncol=jmax)

BEEFPRODYEAR = matrix(nrow=imax+1, ncol=jmax)

BEEFPRODACT = matrix(nrow=imax+1, ncol=jmax)

LWPRODACT = matrix(nrow=imax+1, ncol=jmax)

CARCPRODACT = matrix(nrow=imax+1, ncol=jmax)

LWPROD = matrix(nrow=imax+1, ncol=jmax)

LWPRODYEAR = matrix(nrow=imax+1, ncol=jmax)

LWPRODHERD = NULL

SLAUGHTERDAYACT = matrix(nrow=imax+1, ncol=jmax)

SLAUGHTERDAYACTpl = matrix(nrow=imax+1, ncol=jmax)

SLAUGHTERDAYACTHEIFER = matrix(nrow=imax+1, ncol=jmax)

ENDDAY = c(1,1,1,1,1,1,1,1,1)

SUMFEED1 = matrix(nrow=imax, ncol=jmax)

SUMFEED2 = matrix(nrow=imax, ncol=jmax)

SUMFEED3 = matrix(nrow=imax, ncol=jmax)

SUMFEED4 = matrix(nrow=imax, ncol=jmax)

SUMFEED = matrix(nrow=imax, ncol=jmax)

CUMULFEED1 = matrix(nrow=imax, ncol=jmax)

CUMULFEED2 = matrix(nrow=imax, ncol=jmax)

CUMULFEED3 = matrix(nrow=imax, ncol=jmax)

CUMULFEED4 = matrix(nrow=imax, ncol=jmax)

CUMULFEED = matrix(nrow=imax, ncol=jmax)

FATBURNCUMUL = matrix(nrow=imax+1, ncol=jmax)

HEATBURNCUMUL = matrix(nrow=imax, ncol=jmax)

ALIVE = matrix(nrow=imax+1, ncol=jmax)

FCR = matrix(nrow=imax, ncol=jmax)

FCRBEEF = matrix(nrow=imax, ncol=jmax)

FCRBEEFENDDAY = matrix(nrow=imax, ncol=jmax)

MILKSTART = matrix(nrow=imax, ncol=jmax)

MILKSTARTPR = matrix(nrow=imax, ncol=jmax)

MILKSTARTPRHF = matrix(nrow=imax, ncol=jmax)

METABFEED = matrix(nrow=imax, ncol=jmax)

METABFEEDC = matrix(nrow=imax, ncol=jmax)

METABFEEDCH = matrix(nrow=imax, ncol=jmax)

CHECKHEAT1 = matrix(nrow=imax, ncol=jmax, NA)

CHECKHEAT2 = matrix(nrow=imax, ncol=jmax, NA)

CHECKHEAT3 = matrix(nrow=imax, ncol=jmax, NA)

CHECKCOMP = matrix(nrow=imax, ncol=jmax)

MAXW1 = NULL

CALVESPERANIMAL = NULL

BEEFPRODHERD = NULL

FCRHERDBEEF = NULL

CUMULFEEDHERD = NULL

CUMULFEED1HERD = NULL

CUMULFEED2HERD = NULL

CUMULFEED3HERD = NULL

CUMULFEED4HERD = NULL

ANIMALYEARS = NULL

AVANWEIGHT = matrix(nrow=imax, ncol=jmax)

AVANMETWEIGHT = matrix(nrow=imax, ncol=jmax)

ANIMALINFO = NULL

HERDINFO = NULL

HERDINFO1 = NULL

FATCOMP = matrix(nrow=imax, ncol=jmax)

NONCF = matrix(nrow=imax, ncol=jmax)

PERCFI = matrix(nrow=imax, ncol=jmax)

REPS = matrix(nrow=imax, ncol=jmax)

MEMET = matrix(nrow=imax, ncol=jmax)

MERED = matrix(nrow=imax, ncol=jmax)

PROTNONG = matrix(nrow=imax, ncol=jmax)

HIFM = matrix(nrow=imax, ncol=jmax)

PROTNONGM = matrix(nrow=imax, ncol=jmax)

CPAVG = matrix(nrow=imax, ncol=jmax)

OUTPUTHERDS = NULL # Matrix with information for one herd unit

###########################################################################################

# Dynamic part of the model (animals) #

###########################################################################################

HOUSING1 <- HOUSING # Creates a copy of the vector HOUSING

FEED11 <- FEED1 # Creates a copy of the matrix FEED1

FEED21 <- FEED2 # Creates a copy of the matrix FEED2

FEED31 <- FEED2 # Creates a copy of the matrix FEED3

breakFlaganim <- FALSE # breakFlaganim indicates whether the simulation of an animal should

# be continued (if FALSE) or terminated (if TRUE), e.g. when the

# maximum number of calves is reached per reproductive animal.

for (j in 1:jmax){ # Loop for individual animals starts here (j = jth animal)

imax <- c(imax,2500,2500,2500,2500,2500,2500,2500,2500) # maximum of 2500 day life span

# for productive animals

if(j>1) HOUSING <- HOUSING1[BIRTHDAY[j]:length(HOUSING1)] # adjusts HOUSING for offspring

if(j>1) FEED1 <- FEED11[BIRTHDAY[j]:length(HOUSING1),] # adjusts FEED1 for offspring

if(j>1) FEED2 <- FEED21[BIRTHDAY[j]:length(HOUSING1),] # adjusts FEED2 for offspring

if(j>1) FEED3 <- FEED31[BIRTHDAY[j]:length(HOUSING1),] # adjusts FEED3 for offspring

for (i in 1:imax[j]) { # Loop for daily time step starts here (i = ith day)

breakFlagtime <- FALSE # breakFlagtime indicates whether the simulation of an animal

# should be slaughtered.

###########################################################################################

# 1.5 Initial values for individual animals #

###########################################################################################

# Code below selects the library for genotype (i.e. breed) and sex

if(BREED ==1 & SEX[j] == 0) LIBRARY <- LIBRARY10 else

if(BREED ==1 & SEX[j] == 1) LIBRARY <- LIBRARY11 else

if(BREED ==2 & SEX[j] == 0) LIBRARY <- LIBRARY20 else

if(BREED ==2 & SEX[j] == 1) LIBRARY <- LIBRARY21 else

if(BREED ==3 & SEX[j] == 0) LIBRARY <- LIBRARY30 else

if(BREED ==3 & SEX[j] == 1) LIBRARY <- LIBRARY31 else

if(BREED ==4 & SEX[j] == 0) LIBRARY <- LIBRARY40 else

if(BREED ==4 & SEX[j] == 1) LIBRARY <- LIBRARY41 else

if(BREED ==5 & SEX[j] == 0) LIBRARY <- LIBRARY50

# During sensitivity analysis, the parameters in the library are changed (not used)

LIBRARY <- LIBRARY \* SENSMAT[42:67,s]

# Matrix with time steps (days, starts at day 1)

TIME <- matrix(rep(1:imax[j],jmax), nrow=imax[j], ncol=jmax)

# Matrix with time steps (days, starts at day 0)

TIME2 <- matrix(rep(0:imax[j],jmax), nrow=imax[j]+1, ncol=jmax)

# Matrix with time steps (years, starts at day 1)

TIMEYEAR <- matrix(rep(1:imax[j]/365,jmax), nrow=imax[j], ncol=jmax)

# Matrix with time steps (years, starts at day 0)

TIMEYEAR2 <- matrix(rep(0:imax[j]/365,jmax), nrow=imax[j]+1, ncol=jmax)

# A few parameters from the LIBRARY are re-named here. Values between brackets indicate

# the parameter numbers in Table S2 of the Supplementary Material

REFLC = LIBRARY[1] # [5] Reflectance coat (-)

LC = LIBRARY[2] # [3] Coat length (m)

AREAFACTOR = LIBRARY[3] # [1] Body area (Body area : weight factor)

CBSMAX = LIBRARY[4] # [2] Max. conduction body core ??? skin (W m-2 K-1)

MAXW1[j] = LIBRARY[13] # [20] Maximum adult weight (kg)

MILKPARA = LIBRARY[11] # [13] Lactation curve 1

MILKPARB = LIBRARY[12] # [14] Lactation curve 2

MILKPARC = LIBRARY[27] # [15] Lactation curve 3

RBCSf = LIBRARY[23] # [4] Minimum conduction body core-skin (-)

MAXW = LIBRARY[6] # Maximum adult weight for the Gompertz curve (kg);

# parameter accounts for the reduction parameter (EPAR)

BIRTHW = LIBRARY[7] # [9] Birth weight (kg)

CPAR = LIBRARY[8] # [10] Constant of integration Gompertz curve

DPAR = LIBRARY[9] # [11] Rate constant Gompertz curve

EPAR = LIBRARY[10] # [12] Reduction parameter Gompertz curve

# Initial total body weight (kg live weight), genetic potential

TBW[1,j] = LIBRARY[5]

# Initial carcass weight (kg)

CARCW[1,j] = LIBRARY[5]\*INCARC

# Initial bone weight (kg)

BONETIS[1,j] = CARCW[1,j]\*min(BONEFRACMAX,(BONEGROWTH1 \* SENSMAT[68,s])\*

CARCW[1,j]^-(BONEGROWTH2 \* SENSMAT[69,s]))

# Initial muscle weight (kg)

MUSCLETIS[1,j] = BONETIS[1,j]\*min(LIBRARY[22],(MUSCLEGROWTH1\*SENSMAT[70,s])\*

CARCW[1,j]^2+LIBRARY[22]/100\*CARCW[1,j]+

(MUSCLEGROWTH2\*SENSMAT[71,s]))

# Initial weight intramuscular fat (kg)

INTRAMFTIS[1,j] = ((IMFGROWTH1\*SENSMAT[72,s])\*(BONETIS[1,j]+MUSCLETIS[1,j])^2+

(IMFGROWTH2\*SENSMAT[73,s])\*(BONETIS[1,j]+MUSCLETIS[1,j])-

(IMFGROWTH3\*SENSMAT[74,s]))

# Initial weight of the intermuscular and subcutaneous (i.e. miscellaneous ) fat tissue

# (kg)

MISCFATTIS[1,j] = CARCW[1,j]-BONETIS[1,j]-MUSCLETIS[1,j]-INTRAMFTIS[1,j]

# Initial weight of the non-carcass tissue (kg)

NONCARCTIS[1,j] = TBW[1,j]\*(1-RUMENFRAC)-CARCW[1,j]

# Initial weight of the rumen contents

RUMEN[1,j] = TBW[1,j]\*RUMENFRAC

# Initial weight of lipid in bone tissue (-)

LIPIDBONE[1,j] = BONETIS[1,j]\*(LIBRARY[20]\* log(BONETIS[1,j]))/100

# Initial weight of protein in bone tissue (-)

PROTBONE[1,j] = BONETIS[1,j]\*PROTFRACBONE

# Initial weight of lipid in muscle tissue (-)

LIPIDMUSCLE[1,j] = MUSCLETIS[1,j]\*LIPFRACMUSCLE

# Initial weight of protein in muscle tissue (-)

PROTMUSCLE[1,j] = MUSCLETIS[1,j]\*PROTFRACMUSCLE

# Initial weight of lipid in intramuscular fat tissue (-)

LIPIDIMF[1,j] = INTRAMFTIS[1,j]\*LIPFRACFAT

# Initial weight of protein in intramuscular fat tissue (-)

PROTIMF[1,j] = INTRAMFTIS[1,j]\*PROTFRACFAT

# Initial weight of lipid in the miscellaneous fat tissue (-)

LIPIDFAT[1,j] = MISCFATTIS[1,j]\*LIPFRACFAT

# Initial weight of protein in the miscellaneous fat tissue (-)

PROTFAT[1,j] = MISCFATTIS[1,j]\*PROTFRACFAT

# Initial weight of lipid in the non-carcass tissue (-)

LIPIDNONC[1,j] = 1.00

# Initial weight of protein in the non-carcass tissue (-)

PROTNONC[1,j] = NONCARCTIS[1,j]\*((PROTNONCM1\*SENSMAT[75,s])\*TBW[1,j] +

(PROTNONCM2\*SENSMAT[76,s])) / 100

# The animal is at its potential weight at the first time step.

# Later on, the weight of the animal can deviate from its potential weight, since other

# biophysical factors than the genotype can affect growth.

# Note: LiGAPS-Beef does not account for growth reduction during the gestation period.

# Initial bone weight (kg)

BONETISBF[1,j] = BONETIS[1,j]

# Initial muscle weight (kg)

MUSCLETISBF[1,j] = MUSCLETIS[1,j]

# Initial intramuscular fat weight (kg)

INTRAMFTISBF[1,j] = INTRAMFTIS[1,j]

# Initial miscellaneous fat weight (kg)

MISCFATTISBF[1,j] = MISCFATTIS[1,j]

# Initial non-carcass weight (kg)

NONCARCTISBF[1,j] = NONCARCTIS[1,j]

# Initial total body weight (TBW, in kg live weight)

TBWBF[1,j] = TBW[1,j]

# Initial metabolic body weight (TBW^0.75)

EBWBFMET[1,j] = (TBWBF[1,j]\*(1-RUMENFRAC))^0.75

# Initial fraction of miscellaneous fat in the body

MISCFATFRAC[1,j] = MISCFATTISBF[1,j]/TBWBF[1,j]

# Initial weight lipids in the bone tissue (kg)

LIPIDBONEBF[1,j] = LIPIDBONE[1,j]

# Initial weight lipids in non-carcass tissue (kg)

LIPIDNONCBF[1,j] = LIPIDNONC[1,j]

# Initial weight protein in non-carcass tissue (kg)

PROTNONCBF[1,j] = PROTNONC[1,j]

# Initial weight lipids in muscle tissue (kg)

LIPIDMUSCLEBF[1,j] = LIPIDMUSCLE[1,j]

# Initial weight lipids in the intramuscular fat tissue (kg)

LIPIDIMFBF[1,j] = LIPIDIMF[1,j]

# Initial weight lipids in the miscellaneous fat tissue (kg)

LIPIDFATBF[1,j] = LIPIDFAT[1,j]

# Initial weight of total lipids in the body (kg)

LIPIDTOTW[1,j] = (LIPIDBONEBF[1,j]+LIPIDNONCBF[1,j]+LIPIDMUSCLEBF[1,j]+

LIPIDIMFBF[1,j]+LIPIDFATBF[1,j])

# Initial fraction of lipids in the carcass

LIPIDFRACCARC[1,j] = (LIPIDBONEBF[1,j]+LIPIDMUSCLEBF[1,j]+LIPIDIMFBF[1,j]+

LIPIDFATBF[1,j])/(TBWBF[1,j]-NONCARCTISBF[1,j])

###########################################################################################

HEATTOTALACT[1,j] = 9.00 # Assumption at the first day for heat release.

FATBURNCUMUL[1,j] = 0 # Cumulative amount of fat dissimilated used to maintain body

# temperature (cold stress) is zero (MJ)

HEATBURNCUMUL[1,j] = 0 # Cumulative amount of heat used to maintain body temperature

# (cold stress) is zero (MJ)

ALIVE[1,j] = 1 # The animal is alive at the first time step

# Requirements for gestation:

CALFTBW[1,j] = 0.0 # No calf born yet at the first time step, weight is zero (kg)

CALFNR[1,j] = 0 # Zero calves are born (only for reproductive cows)

GEST1[1,j]= 0 # The total body weight is not higher than the body weight required

# for gestation

GEST2[1,j]= 0 # Gestation not applicable at the first time step

GEST3[1,j]= 1 # Minimum calving interval is not applicable at the first time step

GEST4[1,j]= 0 # Fat tissue in the carcass is assumed to be below the minimum

# required for conception

GEST5[1,j]= 0 # Calves cannot conceive at the first time step and after reaching

# the maximum age for conception

GEST6[1,j]= 1 # Maximum number of calves per cow is not achieved yet

GESTDAY[1,j] = 0 # No gestation at the first time step, days in gestation not

# applicable (days)

NEREQGESTADD[1,j] = 0 # No gestation at the first time step, no NE for gestation (MJ per

# day)

TBWADD[1,j] = 0 # No gestation at the first time step, no weight of foetus (kg)

MILKDAY[1,j] = 0 # No milk production at the first time step, days in milk not

# applicable (days)

MILKWEEK[1,j] = 0 # No milk production at the first time step, days in milk not

# applicable (days)

PARITY1[1,j] = 0 # Cow parity is not equal to or higher than 1 at the first time step

PARITY2[1,j] = 0 # Cow parity is not equal to or higher than 2 at the first time step

PARITY3[1,j] = 0 # Cow parity is not equal to or higher than 3 at the first time step

PARITY4[1,j] = 0 # Cow parity is not equal to or higher than 4 at the first time step

PARITY5[1,j] = 0 # Cow parity is not equal to or higher than 5 at the first time step

PARITY6[1,j] = 0 # Cow parity is not equal to or higher than 6 at the first time step

PARITY7[1,j] = 0 # Cow parity is not equal to or higher than 7 at the first time step

PARITY8[1,j] = 0 # Cow parity is not equal to or higher than 8 at the first time step

###########################################################################################

# 2. Dynamic section #

# (time and animals) #

###########################################################################################

###########################################################################################

# 2.1 Thermoregulation submodel #

###########################################################################################

# Aim: To calculate the maximum and minimum heat release (W m-2) of an animal with its

# environment.

# Five flows of energy between an animal and its environment

# 1. Latent and convective heat release from respiration

# 2. Latent heat release from the skin

# 3. Long wave radiation balance of the coat

# 4. Convective heat losses from the coat

# 5. Solar radiation intecepted by the coat

###########################################################################################

# 2.1.1 Maximum heat release #

###########################################################################################

# Heat release mechanisms of cattle at maximum heat release

TISSUEFRAC = 1.00 # Vasodilatation (0 = minimum and 1 = maximum vasodilatation)

LHRskin = 1.00 # Latent heat release from the skin (0 = basal and 1 = maximum

# physiological 'sweating' rate)

PANTING = RESPDUR\*SENSMAT[77,s] # Panting (0 = basal respiration, 1 = maximum panting)

# Calculations related to weather conditions

# average temperature (degrees Celsius)

TAVGC[i,j] <- (WEATHER$MINT[i]+WEATHER$MAXT[i])/2

# average temperature (degrees Kelvin)

TAVGK[i,j] <- CtoK + TAVGC[i,j]

# saturated vapour pressure air (Pa)

VPSATAIR[i,j] <- 6.1078\*10^((7.5\*TAVGC[i,j])/(TAVGC[i,j]+237.3))\*100

# real vapour pressure air (kPa)

VPAIRTOT[i,j] <- WEATHER$VPR[i]\*1000

# relative humidity (-)

RHAIR[i,j] <- VPAIRTOT[i,j] / VPSATAIR[i,j] \*100

# water vapour density (kg m-3)

RHOVP[i,j] <- VPAIRTOT[i,j]/ (Rwater\*TAVGK[i,j])

# dry air density (kg m-3)

RHODAIR[i,j] <- (P-VPAIRTOT[i,j]) / (Rdair\*TAVGK[i,j])

# air density (kg m-3)

RHOAIR[i,j] <- RHOVP[i,j] + RHODAIR[i,j]

# water vapour density (kg kg-1)

CHIAIR[i,j] <- RHOVP[i,j]\*RHOAIR[i,j]

#########################################################################################

# 1. Latent and convective heat release from respiration #

#########################################################################################

# Animal surface area (m2), McGovern and Bruce (2000)

# This equation corresponds to Eq. 2 of the Supplementary Material

AREA[i,j] = (BODYAREA1\*SENSMAT[78,s])\*TBWBF[i,j]^(BODYAREA2\*SENSMAT[79,s]) \* AREAFACTOR

# This equation corresponds to Eq. 3 of the Supplementary Material

# Animal diameter (m), McGovern and Bruce (2000)

DIAMETER[i,j] = (DIAMETER1\*SENSMAT[80,s])\*TBWBF[i,j]^(DIAMETER2\*SENSMAT[81,s])

# Animal length (m)

LENGTH[i,j] = (AREA[i,j]-0.5\*pi\*DIAMETER[i,j]^2)/(pi\*DIAMETER[i,j])

# Basal respiration rate (min-1), McGovern and Bruce (2000)

brr[i,j] <- (BASALRR1\*SENSMAT[82,s]) \* TBWBF[i,j]^(BASALRR2\*SENSMAT[83,s])

# Basal tidal volume (L) McGovern and Bruce (2000)

btv[i,j] <- (BASALTV\*SENSMAT[84,s]) \* TBWBF[i,j]

# Basal respiration volume (L min-1)

# This equation corresponds to Eq. 5 of the Supplementary Material

brv[i,j] <- brr[i,j]\*btv[i,j]

# Increased respiration volume (L min-1)

# This equation corresponds to Eq. 6 of the Supplementary Material

irv[i,j] <- brv[i,j] + PANTING\*((RESPINCR-1)\*brv[i,j])

# Temperature exhaled air (degrees Celsius), Stevens (1981)

# This equation corresponds to Eq. 7 of the Supplementary Material

Texh[i,j] <- (TEXHALED1\*SENSMAT[85,s]) + (TEXHALED2\*SENSMAT[86,s]) \* TAVGC[i,j] +

exp((TEXHALED3\*SENSMAT[87,s]) \* RHAIR[i,j] + (TEXHALED4\*SENSMAT[88,s]) \* TAVGC[i,j])

# Assumption: exhaled air is saturated with water

# Saturated vapour pressure exhaled air (Pa)

VPSATAIROUT[i,j] <- 6.1078\*10^((7.5\*Texh[i,j])/(Texh[i,j]+237.3))\*100

# Water vapour density exhaled air (kg m-3)

RHOVPOUT[i,j] <- VPSATAIROUT[i,j]/ (Rwater\*(Texh[i,j]+CtoK))

# Dry air density exhaled air (kg m-3)

RHODAIROUT[i,j] <- (P-VPSATAIROUT[i,j]) / (Rdair\*(Texh[i,j]+CtoK))

# Air density exhaled air (kg m-3)

RHOAIROUT[i,j] <- RHOVPOUT[i,j] + RHODAIROUT[i,j]

# Water vapour density exhaled air (kg kg-1)

CHIAIROUT[i,j] <- RHOVPOUT[i,j]\*RHOAIROUT[i,j]

# Air exchange between the animal and its environment (kg air m-2 day-1)

AIREXCH[i,j] <- (irv[i,j]\*60\*24/1000\*RHOAIR[i,j])/AREA[i,j]

# Latent heat release from respiration (W m-2)

LHEATRESP[i,j] <- AIREXCH[i,j] \* L \*(CHIAIROUT[i,j]-CHIAIR[i,j])\* kJdaytoW

# Convective heat release from respiration (W m-2)

CHEATRESP[i,j] <- AIREXCH[i,j] \* Cp \*(Texh[i,j]-TAVGC[i,j]) \* kJdaytoW

# Gross heat loss from the respiratory system (W m-2)

# This equation corresponds to Eq. 8 of the Supplementary Material

TGRESP[i,j] <- LHEATRESP[i,j] + CHEATRESP[i,j]

# NE required for respiration (W m-2), i.e. panting, McGovern and Bruce (2000)

# This equation is similar to Eq. 9 of the Supplementary Material

NERESPWM[i,j] <- 1.1\*(RESPINCR\*brr[i,j])^2.78 \* 10^-5 \* PANTING

# NE required for respiration (kJ NE day-1)

NERESP[i,j] <-NERESPWM[i,j] / kJdaytoW

# Total heat loss from the respiratory system (W m-2)

TNRESP[i,j] <- TGRESP[i,j]-NERESPWM[i,j]

TNRESPH[i,j] <- TNRESP[i,j]

#########################################################################################

# 1a. Skin temperature #

#########################################################################################

# Minimum conductance between body core to skin (W m-2 K-1), McGovern and Bruce (2000)

# This equation corresponds to Eq. 10 of the Supplementary Material

CBSMIN[i,j] = RBCSf/((MINCCS1\*SENSMAT[89,s]) \* TBWBF[i,j]^(MINCCS2\*SENSMAT[90,s]))

# Conduction body core to skin (W m-2 K-1), McGovern and Bruce (2000)

CONDBS[i,j] = CBSMIN[i,j] + TISSUEFRAC\*(CBSMAX-CBSMIN[i,j])

# Notes:

# 100 s m-1 = 0.078 K m2 W-1 (Cena and Clark, 1978)

# Cattle --> 50 s m-1 (Turnpenny, 2000a) --> 0.039 K m-2 W-1 = 25.6 W m-2 K-1

#########################################################################################

# 2. Latent heat release from the skin #

#########################################################################################

# Reduction in coat depth (m), McGovern and Bruce (2000)

DLC[i,j] = (CoatConst \* WEATHER$WIND[i])/((CoatConst \* WEATHER$WIND[i])/LC+1/(ZC\*LC))

# Diffusion constant water vapour in air (m2 s-1), (Denny, 1993)

DIFFC[i,j] = 0.187 \* 10^-9 \* TAVGK[i,j]^2.072

#########################################################################################

# 2a. Coat temperature #

#########################################################################################

# Resistance and conductivity between skin and coat

# Conductance skin to coat (W m-2 K-1)

# This equation corresponds to Eq. 14 of the Supplementary Material

CSC[i,j] = 1 /(RUC \* ZC \* (LC-DLC[i,j]))

# Increase in conductance due to precipitation/rain, Mount and Brown (1982)

CSC[i,j] <- CSC[i,j]/ (1-min(RAINFRAC, WEATHER$RAIN[i]\*RAINFRAC/24))

#########################################################################################

# 3. Long wave radiation from the coat #

#########################################################################################

# Incoming LWR from the sky (W m-2), McGovern and Bruce (2000)

# This equation corresponds to Eq. 19 of the Supplementary Material

LWRSKY[i,j] = (1-WEATHER$OKTA[i]/8)\*(SIGMA\*TAVGK[i,j]^4)\*

(1-0.261\*exp(-0.000777\*(273-TAVGK[i,j])^2)) + (WEATHER$OKTA[i]/8) \*

(SIGMA \* TAVGK[i,j]^4 - 9)

# Incoming LWR from soil surface (W m-2)

LWRENV[i,j] = SIGMA \* TAVGK[i,j]^4

# Cattle in stables do not receive LWR from the sky, but from the roofs and wall of the

# stable they are housed in.

if(HOUSING[i] == 0) LWRSKY[i,j] <- LWRENV[i,j]

#########################################################################################

# 4. Convective heat losses from the coat #

#########################################################################################

# Calculation of the air viscosity, Smits and Dussaunge (2006)

# Average air temperature in degrees Rankine

TAVGR[i,j] = TAVGK[i,j] \* KtoR

# Actual air viscosity (N s-1 m-2), Smits and Dussaunge (2006)

VISCAIR[i,j] =(MuSt\*((0.555\*TR0+ST)/(0.555\*TAVGR[i,j]+ST)\*(TAVGR[i,j]/TR0)^(3/2)))

# Calculation of the Grashof number

# Vapour pressure of the ambient air (mBar)

Ea[i,j] = WEATHER$VPR[i]\*10

# Calculation of the Reynolds number

# Wind speed (m s-1)

WINDSP[i,j] = WEATHER$WIND[i]

# Reynolds number

REYNOLDS[i,j] = WINDSP[i,j] \* DIAMETER[i,j] \* RHOAIR[i,j] / VISCAIR[i,j]

# Calculation step for natural convection

ReH[i,j] = 16\*REYNOLDS[i,j]^2

# Calculation step for forced convection

ReL[i,j] = 0.1\*REYNOLDS[i,j]^2

# Themal conductance of the ambient air (W m-1 K-1)

# This equation corresponds to Eq. 17 of the Supplementary Material

ka[i,j] = 1.5207 \* 10^(-11) \* TAVGK[i,j]^3 - 4.8574 \* 10^(-8) \* TAVGK[i,j]^2 + 1.0184 \*

10^-4 \*TAVGK[i,j] - 0.00039333

#########################################################################################

# 5. Solar radiation intercepted by the coat #

#########################################################################################

# Ah/A factor: Shade area / animal coat area (m2 m-2)

SAAC[i,j] <- WEATHER$AHA[i]

# Incoming direct solar radiation on the soil surface (Wm-2)

SWRS[i,j] <- WEATHER$RAD[i]\*kJdaytoW

# Incoming direct solar radiation on the animal's coat (Wm-2)

# This equation covers part of Eq. 4 of the Supplementary Material

SWRC[i,j] <- SWRS[i,j]\*SAAC[i,j]\*(1-REFLC)

# Indirect solar radiation

if(HOUSING[i]==1) REFLE[i] <- REFLEgrass else

if(HOUSING[i]==2) REFLE[i] <- REFLEconcr else REFLE[i] <- 0

# Incoming indirect solar radiation on an animal's coat (W m-2)

# This equation covers part of Eq. 4 of the Supplementary Material

ISWRC[i,j] <- FRACVEG\*REFLE[i]\*SWRS[i,j]

# Total solar radiation on an animal's coat (W m-2)

SWR[i,j] <- SWRC[i,j] + ISWRC[i,j]

# Heat loss by evaporation of (rain) water (W m-2)

# This equation corresponds to Eq. 20 of the Supplementary Material

RAINEVAP[i,j] <- (RAINEVAP1\*SENSMAT[92,s])\*(LENGTH[i,j]\*DIAMETER[i,j])/AREA[i,j] \*

min(24,WEATHER$RAIN[i]) \* L \* kJdaytoW

# Selects an initial maximum level for heat release and heat production (W m-2)

METABFEED[i,j] <- 170

repeat { # start repeat loop for maximum heat release

#####################################################################################

# 1a. Skin temperature #

#####################################################################################

# Heat transfer from body core to skin (W m-2)

MetheatSKIN[i,j] = METABFEED[i,j] - TNRESP[i,j]

# Skin temperature (degrees Celsius)

# This equation corresponds to Eq. 11 of the Supplementary Material

TskinC[i,j] = TbodyC - MetheatSKIN[i,j]/CONDBS[i,j]

METABFEEDCH[i,j] = METABFEED[i,j]

#####################################################################################

# 2. Latent heat release from the skin #

#####################################################################################

# Maximum physological latent heat release from skin (W m-2)

# This equation corresponds to Eq. 12 of the Supplementary Material

LASMAXPHYS[i,j] = LASMIN + LIBRARY[24]\*exp(LIBRARY[25]\*(TskinC[i,j]-LIBRARY[26])) \*

L/3600

# Resistance vapour transfer (s m-1), Thompson et al. (2011)

RV[i,j] = (LC-DLC[i,j])/(DIFFC[i,j]\*

(1+1.54\*((LC-DLC[i,j])/DIAMETER[i,j]) \*

(TskinC[i,j]-min(TAVGC[i,j],TskinC[i,j]))^0.7))

# Saturated vapour pressure skin (Pa)

VPSKINTOT[i,j] = 6.1078\*10^((7.5\*TskinC[i,j])/(TskinC[i,j]+237.3))\*100

# Maximum latent heat release from skin due to the ambient environment (W m-2)

# This equation corresponds to Eq. 13 of the Supplementary Material

LASMAXENV[i,j] = (RHOAIR[i,j] \* Cp \* 1000) / GAMMA \* (VPSKINTOT[i,j]-VPAIRTOT[i,j]) /

RV[i,j]

# Maximum latent heat release from skin (W m-2)

LASMAXCORR[i,j] = min(LASMAXPHYS[i,j],LASMAXENV[i,j])

# Actual latent heat release from skin (W m-2)

ACTSW[i,j] = LASMIN + LHRskin \* (LASMAXCORR[i,j]-LASMIN)

ACTSWH[i,j] = ACTSW[i,j]

#####################################################################################

# 2a. Coat temperature #

#####################################################################################

# Heat transfer from the skin to the coat (W m-2)

MetheatCOAT[i,j] = MetheatSKIN[i,j] - ACTSW[i,j]

# Coat temperature (degrees Celsius)

# This equation corresponds to Eq. 15 of the Supplementary Material

TcoatC[i,j] = TskinC[i,j] - MetheatCOAT[i,j]/CSC[i,j]

# Coat temperature (degrees Kelvin)

TcoatK[i,j] = TcoatC[i,j] + CtoK

#####################################################################################

# 3. Long wave radiation from the coat #

#####################################################################################

# LWR release from the coat (W m-2)

LB[i,j] = EMISS \* SIGMA \* TcoatK[i,j]^4

# LWR balance (W m-2) (net energy loss is a negative value!)

# This equation corresponds partly to Eq. 18 of the Supplementary Material

LWRCOAT[i,j] = (EMISS \* ((LWRSKY[i,j]+LWRENV[i,j])/2) - LB[i,j]) \*

(1-min(RAINFRAC,WEATHER$RAIN[i]\*RAINFRAC/24))

LWRCOATH[i,j] = LWRCOAT[i,j]

#####################################################################################

# 4. Convective heat losses from the coat #

#####################################################################################

# Vapour pressure at the skin (mBar)

Ec[i,j] = ((6.1078\*10^((7.5\*TskinC[i,j])/(TskinC[i,j]+237.3)))+Ea[i,j])/2

# Grashof number

GRASHOF[i,j] = (GRAV\*DIAMETER[i,j]^3\*P/100\*(TcoatC[i,j]-TAVGC[i,j])+Schmidt\*

(Ec[i,j]\*TcoatC[i,j]-Ea[i,j]\*TAVGC[i,j]))/

(273\*P/100\*VISCAIR[i,j]^2)

# Calculation of the Nusselt number, Turnpenny et al. (2000a)

if(GRASHOF[i,j]>ReH[i,j]) NUSSELT[i,j] <- 0.48\*GRASHOF[i,j]^0.25 else

if(GRASHOF[i,j]<ReL[i,j]) NUSSELT[i,j] <- 0.0112\*REYNOLDS[i,j]^0.875 else

NUSSELT[i,j] <- max(0.48\*GRASHOF[i,j]^0.25,0.0112\*REYNOLDS[i,j]^0.875)

# Heat transfer from the coat by convection (W m-2)

# This equation corresponds partly to Eq. 16 of the Supplementary Material

CONVCOAT[i,j] = (ka[i,j] \* NUSSELT[i,j]) / DIAMETER[i,j] \*(TcoatC[i,j]-TAVGC[i,j]) /

(1-min(RAINFRAC,WEATHER$RAIN[i]\*RAINFRAC/24))

CONVCOATH[i,j] = CONVCOAT[i,j]

#####################################################################################

# Synthesis #

#####################################################################################

# Heat balance (W m-2)

# This equation is similar to Eq. 1 of the Supplementary Material

MetheatBAL[i,j] <- (MetheatCOAT[i,j] + SWR[i,j] - RAINEVAP[i,j] + LWRCOAT[i,j] -

CONVCOAT[i,j] )

# If the estimate for heat production is too high, it is decreased

if(MetheatBAL[i,j] > 0.1) METABFEED[i,j] <- (METABFEED[i,j]-0.1\*MetheatBAL[i,j])

# If the estimate for heat production is too low, it is increased

if(MetheatBAL[i,j] < -0.1) METABFEED[i,j] <-(METABFEED[i,j]-0.1\*MetheatBAL[i,j])

# Heat release and production

Metheatopt[i,j] <- METABFEED[i,j]

# If the heat release and production differ more than 0.1 W m-2, the loop is run

# another time

if(MetheatBAL[i,j] < 0.1 & MetheatBAL[i,j] > -0.1) CHECKHEAT1[i,j] <- "CORRECT" else

CHECKHEAT1[i,j] <- "FALSE"

if(CHECKHEAT1[i,j] == "CORRECT") {break}

} # end repeat loop for maximum heat release

###########################################################################################

# 2.1.2 Minimum heat release #

###########################################################################################

# Heat release mechanisms of cattle at minimum heat release

TISSUEFRAC = 0.0 # Vasodilatation (0 = minimum and 1 = maximum vasodilatation)

LHRskin = 0.0 # Latent heat release (0 = minimum and 1 = maximum

# physiological 'sweating' rate)

PANTING = 0.0 # Panting (0 = basal respiration, 1 is maximum panting)

#########################################################################################

# 1. Latent and convective heat release from respiration #

#########################################################################################

# Actual respiration rate (L min-1)

irv[i,j] <- brv[i,j] + PANTING\*((RESPINCR-1)\*brv[i,j])

# Air exchange between the animal and its environment (kg air m-2 day-1)

AIREXCH[i,j] <- (irv[i,j]\*60\*24/1000\*RHOAIR[i,j])/AREA[i,j]

# Latent heat release via respiratory system (W m-2)

LHEATRESP[i,j] <- AIREXCH[i,j] \* L \*(CHIAIROUT[i,j]-CHIAIR[i,j])\*kJdaytoW

# Concective heat release via respiratory system (W m-2)

CHEATRESP[i,j] <- AIREXCH[i,j] \* Cp \*(Texh[i,j]-TAVGC[i,j])\*kJdaytoW

# Gross heat loss from the respiratory system (W m-2)

TGRESP[i,j] <- LHEATRESP[i,j] + CHEATRESP[i,j]

# Total heat loss from the respiratory system (W m-2)

TNRESP[i,j] <- TGRESP[i,j]

#########################################################################################

# 1a. Skin temperature #

#########################################################################################

# Conductance body core to skin (W m-2 K-1)

CONDBS[i,j] = CBSMIN[i,j]

#########################################################################################

# 2. Latent heat release from the skin #

#########################################################################################

# Actual latent heat release from the skin (W m-2)

ACTSW[i,j] = LASMIN

# Selects an initial minimum level for heat release and heat production (W m-2)

METABFEEDC[i,j] <-80

repeat { # start repeat loop for minimum heat release

#######################################################################################

# 1a. Skin temperature #

#######################################################################################

# Heat transfer from the body core to skin (W m-2)

MetheatSKIN[i,j] = METABFEEDC[i,j] - TNRESP[i,j]

# Skin temperature (degrees Celsius)

TskinC[i,j] = TbodyC - MetheatSKIN[i,j]/CONDBS[i,j]

TskinCH[i,j] = TskinC[i,j]

#######################################################################################

# 2a. Coat temperature #

#######################################################################################

# Heat transfoer from skin to coat (W m-2)

MetheatCOAT[i,j] = MetheatSKIN[i,j] - ACTSW[i,j]

# Coat temperature (degrees Celsius)

TcoatC[i,j] = TskinC[i,j] - MetheatCOAT[i,j]/CSC[i,j]

# Coat temperature (degrees Kelvin)

TcoatK[i,j] = TcoatC[i,j] + CtoK

TcoatCH[i,j] = TcoatC[i,j]

#######################################################################################

# 3. Long wave radiation from the coat #

#######################################################################################

# LWR release from the coat (W m-2)

LB[i,j] = EMISS \* SIGMA \* TcoatK[i,j]^4

# LWR from coat to the environment (net energy loss is a negative value) (W m-2)

LWRCOAT[i,j] = (EMISS \* ((LWRSKY[i,j]+LWRENV[i,j])/2) - LB[i,j]) \*

(1-min(RAINFRAC,WEATHER$RAIN[i]\*RAINFRAC/24))

#######################################################################################

# 4. Convective heat loss from the coat #

#######################################################################################

# Vapour pressure at the coat (mBar)

Ec[i,j] = ((6.1078\*10^((7.5\*TcoatC[i,j])/(TcoatC[i,j]+237.3)))+Ea[i,j])/2

# Grashof number

GRASHOF[i,j] = (GRAV\*DIAMETER[i,j]^3\*P/100\*(TcoatC[i,j]-TAVGC[i,j])+Schmidt\*

(Ec[i,j]\*TcoatC[i,j]-Ea[i,j]\*TAVGC[i,j]))/(273\*P/100\*VISCAIR[i,j]^2)

# Calculation of the Nusselt number, Turnpenny et al. (2000a)

if(GRASHOF[i,j]>ReH[i,j]) NUSSELT[i,j] <- 0.48\*GRASHOF[i,j]^0.25 else

if(GRASHOF[i,j]<ReL[i,j]) NUSSELT[i,j] <- 0.0112\*REYNOLDS[i,j]^0.875 else

NUSSELT[i,j] <- max(0.48\*GRASHOF[i,j]^0.25,0.0112\*REYNOLDS[i,j]^0.875)

# Convective heat transfer between coat and air (W m-2)

CONVCOAT[i,j] = (ka[i,j] \* NUSSELT[i,j]) / DIAMETER[i,j] \*(TcoatC[i,j]-TAVGC[i,j]) /

(1-min(RAINFRAC,WEATHER$RAIN[i]\*RAINFRAC/24))

#######################################################################################

# Synthesis #

#######################################################################################

# Heat balance (W m-2)

# This equation is similar to Eq. 1 of the Supplementary Material

MetheatBAL[i,j] <- (MetheatCOAT[i,j] + SWR[i,j] - RAINEVAP[i,j] + LWRCOAT[i,j] -

CONVCOAT[i,j])

# If the estimate for heat production is too high, it is decreased

if(MetheatBAL[i,j] > 0.1) METABFEEDC[i,j] <- (METABFEEDC[i,j]-0.05\*MetheatBAL[i,j])

# If the estimate for heat production is too low, it is increased

if(MetheatBAL[i,j] < -0.1) METABFEEDC[i,j] <-(METABFEEDC[i,j]-0.05\*MetheatBAL[i,j])

# Heat release and production

Metheatcold[i,j] <- METABFEEDC[i,j]

# If the heat release and production differ more than 0.1 W m-2, the loop is run

# another time

if(MetheatBAL[i,j] < 0.1 & MetheatBAL[i,j] > -0.1) CHECKHEAT2[i,j] <- "CORRECT" else

CHECKHEAT2[i,j] <- "FALSE"

if(CHECKHEAT2[i,j] == "CORRECT") {break}

}

#########################################################################################

# 2.2 Energy and protein utilisation sub-model #

#########################################################################################

######################

# Growth (potential) #

######################

# TBW and carcass weight

# Gompertz curve with breed specific parameters, total body weight (TBW) (kg live

# weight per animal)

# This equation corresponds to Eq. 31 in the Supplementary Material

TBW[i+1,j] = (BIRTHW+(MAXW-BIRTHW)\*exp(-CPAR\*exp(TIME[i,j]/365\*-DPAR)))-EPAR

# Carcass weight (kg per animal)

# This equation corresponds to Eq. 32 in the Supplementary Material

CARCW[i+1,j] = TBW[i+1,j]\*INCARC+TBW[i+1,j]\*(LIBRARY[21]-INCARC)\*

(TBW[i+1,j]-BIRTHW)/(MAXW1[j]-BIRTHW)

# Records the highest average daily gain (ADG) of an animal during its lifespan (kg LW

# day-1)

ADGHIGH[i+1,j] = max(ADGHIGH[i,j],TBW[i+1,j]-TBW[i,j])

# Bone and muscle weight

# Derivative potential growth bone tissue (kg day-1), according to Gompertz curve

# This equation contains Eq. 33 of the Supplementary Material

DERBONE[i,j] = CARCW[i+1,j]\*min(BONEFRACMAX,(BONEGROWTH1 \* SENSMAT[68,s])\*

CARCW[i+1,j]^-(BONEGROWTH2 \* SENSMAT[69,s]))-CARCW[i,j]\*

min(BONEFRACMAX, (BONEGROWTH1 \* SENSMAT[68,s])\*CARCW[i,j]^

-(BONEGROWTH2 \* SENSMAT[69,s]))

# Derivative potential growth muscle tissue (kg day-1)

# This equation contains Eqs 34 and 35 of the Supplementary Material

DERMUSCLE[i,j] = DERBONE[i,j]\*min(LIBRARY[22],(MUSCLEGROWTH1\*SENSMAT[70,s])\*

CARCW[i+1,j]^2+LIBRARY[22]/100\*CARCW[i+1,j]+

(MUSCLEGROWTH2\*SENSMAT[71,s]))

# Weight bone tissue (kg per animal)

# Note: new state = previous state + rate of change over a time step

BONETIS[i+1,j] = BONETIS[i,j] + DERBONE[i,j]

# Weight muscle tissue (kg per animal)

MUSCLETIS[i+1,j] = MUSCLETIS[i,j] + DERMUSCLE[i,j]

# Intramuscular fat, miscellaneous fat and non-carcass tissues

# Derivative potential growth intramuscular fat (kg day-1)

# This equation contains Eq. 36 of the Supplementary Material

DERINTRAMF[i,j] = ((IMFGROWTH1\*SENSMAT[72,s])\*(BONETIS[i+1,j]+MUSCLETIS[i+1,j])^2+

(IMFGROWTH2\*SENSMAT[73,s])\*(BONETIS[i+1,j]+MUSCLETIS[i+1,j])-

(IMFGROWTH3\*SENSMAT[74,s]))-((IMFGROWTH1\*SENSMAT[72,s])\*

(BONETIS[i,j]+MUSCLETIS[i,j])^2+(IMFGROWTH2\*SENSMAT[73,s])\*

(BONETIS[i,j]+MUSCLETIS[i,j])-(IMFGROWTH3\*SENSMAT[74,s]))

# Derivative potential growth subcutaneous and intermuscular (i.e. miscellaneous) fat

# tissue (kg day-1)

# This equation corresponds to Eq. 37 of the Supplementary Material

DERMISCFAT[i,j] = (CARCW[i+1,j]-CARCW[i,j])-DERBONE[i,j] - DERMUSCLE[i,j] -

DERINTRAMF[i,j]

# Derivative potential growth non carcass tissue (kg day-1)

DERNONC[i,j] = (TBW[i+1,j]\*(1-RUMENFRAC)-TBW[i,j]\*(1-RUMENFRAC))-

(CARCW[i+1,j]-CARCW[i,j])

# Derivative potential growth of the rumen (kg day-1)

# This equation is similar to Eq. 39 of the Supplementary Material

DERRUMEN[i,j] = (TBW[i+1,j]\*RUMENFRAC-TBW[i,j]\*RUMENFRAC)

# Derivative potential growth of all body tissues (kg day-1)

DERTOTAL[i,j] = DERBONE[i,j]+DERMUSCLE[i,j]+DERINTRAMF[i,j]+DERMISCFAT[i,j]+

DERNONC[i,j]+DERRUMEN[i,j]

# Weight intramuscular fat tissue (kg per animal)

INTRAMFTIS[i+1,j] = INTRAMFTIS[i,j] + DERINTRAMF[i,j]

# Weight miscellaneous fat tissue (kg per animal)

MISCFATTIS[i+1,j] = MISCFATTIS[i,j] + DERMISCFAT[i,j]

# Weight non-carcass tissue (kg per animal)

NONCARCTIS[i+1,j] = NONCARCTIS[i,j] + DERNONC[i,j]

# Weight rumen content (kg per animal)

RUMEN[i+1,j] = RUMEN[i,j] + DERRUMEN[i,j]

# Check: sum of tissues and rumen content must correspond to the TBW (kg per animal)

TBWCHECK[i+1,j] = BONETIS[i+1,j]+ MUSCLETIS[i+1,j]+INTRAMFTIS[i+1,j]+

MISCFATTIS[i+1,j]+NONCARCTIS[i+1,j]+RUMEN[i+1,j]

# Fraction lipid in bone tissue (-)

# This equation corresponds to Eq. 40 of the Supplementary Material

LIPIDFRACBONE[i,j] = (LIBRARY[20]\* log10(BONETIS[i,j]))/100

# Fraction lipid accreted in new non-carcass tissue (-)

# This equation corresponds to Eq. 41 of the Supplementary Material

LIPIDFRACNONC[i,j] = min(LIPNONCMAX,max(LIPNONCMIN, LIPNONCMIN+(NONCARCTIS[i,j]/

(LIBRARY[13]\*(1-RUMENFRAC)\*(1-LIBRARY[21])))^2\*LIPNONCMAX))

# Fraction protein accreted in new non-carcass tissue (-)

# This equation corresponds to Eq. 42 of the Supplementary Material

PROTFRACNONC[i,j] = ((PROTNONCM1\*SENSMAT[75,s])\*TBW[i,j] +

(PROTNONCM2\*SENSMAT[76,s])) / 100

# Weight of lipids and protein in body tissues

# Note: new state = previous state + rate of change over one time step

# Weight of lipids in bone tissue (kg per animal)

LIPIDBONE[i+1,j] = LIPIDBONE[i,j] + DERBONE[i,j]\*LIPIDFRACBONE[i,j]

# Weight of protein in bone tissue (kg per animal)

PROTBONE[i+1,j] = PROTBONE[i,j] + DERBONE[i,j]\*PROTFRACBONE

# Energy (combustion energy + inefficiency) accreted in bone tissue (MJ per day)

# Note: 53.5 MJ kg-1 for lipid, 44.0 MJ kg-1 gross energy for protein

ENGRBONE[i+1,j] = DERBONE[i,j]\*LIPIDFRACBONE[i,j]\*GELIPID/LIPIDEFF +

DERBONE[i,j] \* PROTFRACBONE\*GEPROT/PROTEFF

# Weight of lipids in bone tissue (kg per animal)

LIPIDMUSCLE[i+1,j] = LIPIDMUSCLE[i,j] + DERMUSCLE[i,j]\*LIPFRACMUSCLE

# Weight of protein in muscle tissue (kg per animal)

PROTMUSCLE[i+1,j] = PROTMUSCLE[i,j] + DERMUSCLE[i,j]\*PROTFRACMUSCLE

# Energy (combustion energy + inefficiency) accreted in muscle tissue (MJ per day)

ENGRMUSCLE[i+1,j] = DERMUSCLE[i,j]\*LIPFRACMUSCLE\*GELIPID/LIPIDEFF +

DERMUSCLE[i,j] \* PROTFRACMUSCLE\*GEPROT/PROTEFF

# Weight of lipids in the intermuscular fat tissue (kg per animal)

LIPIDIMF[i+1,j] = LIPIDIMF[i,j] + DERINTRAMF[i,j]\*LIPFRACFAT

# Weight of protein in the intermuscular fat tissue (kg per animal)

PROTIMF[i+1,j] = PROTIMF[i,j] + DERINTRAMF[i,j]\*PROTFRACFAT

# Energy (combustion energy + inefficiency) accreted in the intermuscular fat tissue

# (MJ per day)

ENGRIMF[i+1,j] = DERINTRAMF[i,j]\*LIPFRACFAT\*GELIPID/LIPIDEFF +

DERINTRAMF[i,j] \* PROTFRACFAT\*GEPROT/PROTEFF

# Weight of lipids in the miscellaneous fat tissue (kg per animal)

LIPIDFAT[i+1,j] = LIPIDFAT[i,j] + DERMISCFAT[i,j]\*LIPFRACFAT

# Weight of protein in the miscellaneous fat tissue (kg per animal)

PROTFAT[i+1,j] = PROTFAT[i,j] + DERMISCFAT[i,j]\*PROTFRACFAT

# Energy (combustion energy + inefficiency) accreted in miscellaneous fat tissue

# (MJ per day)

ENGRFAT[i+1,j] = DERMISCFAT[i,j]\*LIPFRACFAT\*GELIPID/LIPIDEFF +

DERINTRAMF[i,j] \* PROTFRACFAT\*GEPROT/PROTEFF

# Weight of lipids in the non-carcass tissue (kg per animal)

LIPIDNONC[i+1,j] = LIPIDNONC[i,j] + DERNONC[i,j] \* LIPIDFRACNONC[i,j]

# Weight of protein in the non-carcass tissue (kg per animal)

PROTNONC[i+1,j] = PROTNONC[i,j] + DERNONC[i,j] \* PROTFRACNONC[i,j]

# Energy (combustion energy + inefficiency) accreted in non-carcass tissue (MJ per day)

ENGRNONC[i+1,j] = DERNONC[i,j]\*LIPIDFRACNONC[i,j]\*GELIPID/LIPIDEFF +

DERNONC[i,j] \* PROTFRACNONC[i,j]\*GEPROT/PROTEFF

# Total net energy (NE) to realise potential growth (MJ per day)

# This equation is similar to Eq. 43 of the Supplementary Material

ENGRTOTAL[i+1,j] = ENGRBONE[i+1,j]+ENGRNONC[i+1,j]+ENGRMUSCLE[i+1,j]+

ENGRIMF[i+1,j]+ENGRFAT[i+1,j]

ENGRTOTALORIG[i+1,j] = ENGRTOTAL[i+1,j]

# Records the highest NE for growth throughout an animals life span (MJ per day)

ENGRTOTALHIGH[i+1,j] = if(TIME[i,j] <= WEANINGTIME) ENGRTOTALHIGH[i+1,j] <- 0 else

ENGRTOTALHIGH[i+1,j] <- max(ENGRTOTALHIGH[i,j], ENGRTOTAL[i+1,j])

# Records the highest NE for growth throughout an animals life span, including

# compensatory growth (MJ per day)

# This equation corresponds to Eq. 45 of the Supplementary Material, and contains

# Eq. 44.

ENGRTOTALHIGH1[i+1,j] = ENGRTOTALHIGH[i+1,j] \*

min(1.0,(1-(TBWBF[i,j]/TBW[i,j]))\*COMPFACT)

# Relative proportion between NE for growth with and without compensatory growth (-)

REL[i+1,j] = ENGRTOTALHIGH1[i+1,j]/ENGRTOTAL[i+1,j]

if(REL[i+1,j] <1) REL[i+1,j] <- 1

# The NE for growth based on the genetic potential and the scope for compensatory

# growth (MJ per day)

if(TIME[i,j] <= WEANINGTIME) ENGRTOTAL[i+1,j] <- ENGRTOTAL[i+1,j] else

ENGRTOTAL[i+1,j] <- max(ENGRTOTAL[i+1,j], min(1.0,(1-(TBWBF[i,j]/TBW[i,j]))\*

COMPFACT)\*ENGRTOTALHIGH[i+1,j])

# Percentage of lipid in the carcass (consists of bone tissue, muscle tissue, and fat

# tissues) (%)

LIPIDFRACCARC[i+1,j] = (LIPIDBONE[i+1,j]+LIPIDMUSCLE[i+1,j]+LIPIDIMF[i+1,j]+

LIPIDFAT[i+1,j])/(TBW[i+1,j]-NONCARCTIS[i+1,j]-RUMEN[i+1,j])\*100

#########################################################################################

# Maintenance #

###############

# Energy balance

# NE for (fasting) maintenance (kJ per animal per day)

NEMAINT[i,j] = EBWBFMET[i,j] \* NEm \* LIBRARY[18]

# NE for (fasting) maintenance (W m-2)

NEMAINTWM[i,j] = NEMAINT[i,j] \* 1000 / (3600 \* 24 \* AREA[i,j])

# Protein balance

# Dermal loss of protein (CSIRO, 2007) (g protein day-1)

PROTDERML[i,j] <- DERMPL\* EBWBFMET[i,j]

# Protein requirement for (fasting) maintenance (CSIRO, 2007) (g protein day-1)

# Note: PROTNE = 2g N / 4.18 = 0.478

PROTMAINT[i,j] <- NEMAINT[i,j] \* PROTNE / 1000 \* NtoCP

#########################################################################################

# Physical activity #

#####################

# Energy balance

# NE for physical activity (kJ per animal per day), function of metabolic body weight

# Note: If necessary, the line of code below can also be written as a function of the

# total body weight (TBW)

if(HOUSING[i] >= 1) NEPHYSACT[i,j] = EBWBFMET[i,j] \* NEpha else NEPHYSACT[i,j] <- 0

# NE for physical activity (W m-2)

NEPHYSACTWM[i,j] = NEPHYSACT[i,j] \* 1000 / (3600 \* 24 \* AREA[i,j])

# Protein balance

# Protein requirement for physical activity (g protein day-1)

# Note: PROTNE = 2g N / 4.18 = 0.478

PROTPHACT[i,j] <- NEPHYSACT[i,j] \* PROTNE / 1000 \* NtoCP

#########################################################################################

# Gestation #

#############

# Cows can conceive if seven requirements are met (0= no conception, 1 = conception):

# 1. The TBW must be higher than a specific fraction of their maximum adult TBW

if(TBWBF[i,j]<(LIBRARY[17]\*MAXW1[j])) GEST1[i,j] <- 0 else GEST1[i,j] <- 1

# 2. Cows cannot conceive while gestating

if(CALFTBW[i,j]==0) GEST2[i,j] <- 1 else GEST2[i,j] <- 0

# 3. Cows cannot conceive directly after parturition (depending on the minimum

# calving interval)

if(sum(CALFTBW[i,j])-sum(CALFTBW[max(0,i-(GESTINTERVAL-GestPer-1)),j])==0)

GEST3[i,j] <- 1 else GEST3[i,j] <- 0

# 4. Cows can conceive if the fat tissues cover a certain fraction of the carcass

# tissue

if((MISCFATTISBF[i,j]+INTRAMFTISBF[i,j])/

(TBWBF[i,j]-NONCARCTISBF[i,j]-RUMEN[i,j]) < LIBRARY[19])

GEST4[i,j] <- 0 else GEST4[i,j] <- 1

# 5. Cattle conceive at a specific date (STDOY), in case of seasonal calving

# Note: for year-round calving, GEST5 must be 1

if(DOY[i] == STDOY+(GESTINTERVAL-GestPer)) GEST5[i,j] <- 1 else GEST5[i,j] <- 1

# 6. Cows cannot conceive after their maximum age for conception

if(TIME[i,j]/365<MAXCONCAGE) GEST5[i,j] <- GEST5[i,j] else GEST5[i,j] <- 0

# 7. Cows cannot conceive anymore if the maximum number of calves per cow is achieved

# If not eight calves after 10 years, reduce MAXCALFNR

if(TIME[i,j]/365>MAXCONCAGE) MAXCALFNR <- CALFNR[i,j] else MAXCALFNR <- MAXCALFNR

if(CALFNR[i,j] < MAXCALFNR) GEST6[i+1,j] <- 1 else GEST6[i+1,j] <- 0

# Check whether a cow meets all seven conditions (0= no conception, 1 = conception)

GEST[i,j] <- GEST1[i,j] \* GEST2[i,j] \* GEST3[i,j] \* GEST4[i,j] \* GEST5[i,j] \*

GEST6[i+1,j] \* LIBRARY[14] \* REPRODUCTIVE[j]

# Counts number of calves (incl. gestation) per cow

CALFNR[i+1,j] = GEST[i,j] + CALFNR[i,j]

# Gestation starts when all seven requirements are met

if(GEST[i,j]==1) GESTDAY[i+1,j] <- 1 else

if (GESTDAY[i,j]>0) GESTDAY[i+1,j] <- GESTDAY[i,j] + 1 else GESTDAY[i+1,j] <- 0

if(GEST[i,j]==1) GESTDAY[i,j] <-0

# Breed- and sex-specific birth weights (kg live weight)

if(BREED == 1) BIRTHW1[i,j] <- LIBRARY10[5]-SEX[CALFNR[i,j]+1]\*

(LIBRARY10[5]-LIBRARY11[5]) else

if(BREED == 2) BIRTHW1[i,j] <- LIBRARY20[5]-SEX[CALFNR[i,j]+1]\*

(LIBRARY20[5]-LIBRARY21[5]) else

if(BREED == 3) BIRTHW1[i,j] <- LIBRARY30[5]-SEX[CALFNR[i,j]+1]\*

(LIBRARY30[5]-LIBRARY31[5]) else

if(BREED == 4) BIRTHW1[i,j] <- LIBRARY40[5]-SEX[CALFNR[i,j]+1]\*

(LIBRARY40[5]-LIBRARY41[5]) else

if(BREED == 5) BIRTHW1[i,j] <- LIBRARY50[5]-SEX[CALFNR[i,j]+1]\*

(LIBRARY50[5]-LIBRARY50[5])

# Code for sensitivity analysis on birth weight (not used in this version)

BIRTHW1[i,j] <- BIRTHW1[i,j] \* SENSMAT[46,s]

# Net energy (NE) requirements for gestation, Fox et al. (1988)

# This is an empirical equation.

# This equation is similar to Eq. 28 and 29 in the Supplementary Material

if(GESTDAY[i+1,j] >=1 & GESTDAY[i+1,j] <= GestPer)

NEREQGEST[i,j] <- (SENSMAT[93,s]) \*((9.527001\*(0.0000000681-0.000000000197\*

GESTDAY[i,j])\*(exp((0.0885-0.0001282\*GESTDAY[i,j])\*

GESTDAY[i,j])) + 5.505\*((0.00003452-0.0000001094\*

GESTDAY[i,j])\*(exp((0.0589-0.00009334\*GESTDAY[i,j])\*

GESTDAY[i,j]))))\*CALTOJOULE\*10\*(BIRTHW1[i,j]/37.2)\*0.6) else

NEREQGEST[i,j] = 0

# Note: The efficiency of energy accretion gestation is only 14% (Jarrige, 1989,

# Rattray et al., 1974) for the calf, and 9.33% for extra tissue of the

# reproductive cow (Jarrige, 1989)

# Heat production from gestation (MJ per cow per day)

HEATGEST[i,j] = NEREQGEST[i,j] \* NEIEFFGEST

# Cumulative NE during gestation (MJ)

NEREQGESTADD[i+1,j] = NEREQGESTADD[i,j]+NEREQGEST[i,j]

# Breed- and sex-specific NE requirements for the complete gestation period

if(BREED == 1 & SEX[CALFNR[i,j]+1] == 0) NEREQGESTTOT = 58.658\*LIBRARY10[7]+0.5502

if(BREED == 1 & SEX[CALFNR[i,j]+1] == 1) NEREQGESTTOT = 58.658\*LIBRARY11[7]+0.5502

if(BREED == 2 & SEX[CALFNR[i,j]+1] == 0) NEREQGESTTOT = 58.658\*LIBRARY20[7]+0.5502

if(BREED == 2 & SEX[CALFNR[i,j]+1] == 1) NEREQGESTTOT = 58.658\*LIBRARY21[7]+0.5502

if(BREED == 3 & SEX[CALFNR[i,j]+1] == 0) NEREQGESTTOT = 58.658\*LIBRARY30[7]+0.5502

if(BREED == 3 & SEX[CALFNR[i,j]+1] == 1) NEREQGESTTOT = 58.658\*LIBRARY31[7]+0.5502

if(BREED == 4 & SEX[CALFNR[i,j]+1] == 0) NEREQGESTTOT = 58.658\*LIBRARY40[7]+0.5502

if(BREED == 4 & SEX[CALFNR[i,j]+1] == 1) NEREQGESTTOT = 58.658\*LIBRARY41[7]+0.5502

if(BREED == 5 & SEX[CALFNR[i,j]+1] == 0) NEREQGESTTOT = 58.658\*LIBRARY50[7]+0.5502

# The weight of the foetus is calculated from the cumulative NE for gestation and the

# complete NE required during the gestation period (kg).

CALFTBW[i+1,j] = NEREQGESTADD[i+1,j]/NEREQGESTTOT\*BIRTHW1[i,j]

# At the end of the gestation period, the calf reaches its birth weight (kg live

# weight)

if(GESTDAY[i+1,j] >=1 & GESTDAY[i+1,j] <= GestPer)

CALFTBW[i+1,j] <- CALFTBW[i+1,j] else CALFTBW[i+1,j] <- 0

# The (cumulative) NE requirements for gestation stop after parturition

if((CALFTBW[i,j]-CALFTBW[i+1,j])>BIRTHW1[i,j]-1) NEREQGESTADD[i+1,j] <- 0

# Additional TBW of the cow, without an increase in the NE requirements for

# maintenance. The weight increase of the cow includes the weight of the foetus and

# the concepta (Jarrige, 1986, p. 99)

TBWADD[i+1,j] = CALFTBW[i+1,j] \* FtoConcW

# Protein balance

# Protein requirements for gestation (g protein day-1)

# Note: \* based on total NE and protein requirements (CSIRO, 2007)

# \* the conversion is 4.322 g protein per MJ NE for gestation

# \* the formula given in CSIRO (2007) is assumed to present the gross protein

# requirement for gestation

PROTGESTG[i,j] <- NEREQGEST[i,j] \* CPGEST

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# Milk production #

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# Days in milk, milk production starts at parturition

if(GESTDAY[i,j] == GestPer-1) MILKDAYST[i,j] <- 1 else MILKDAYST[i,j] <- 0

# Start of milk production after parturition

if (MILKDAYST[i,j]==1) ADDMILK2[i,j] <- 1 else ADDMILK2[i,j] <- 0

# Adds up days after parturition

if (MILKDAY[i,j] >0 ) ADDMILK1[i,j] <- 1 else ADDMILK1[i,j] <- 0

# Days after parturition

MILKDAY[i+1,j] = MILKDAY[i,j] + ADDMILK1[i,j] + ADDMILK2[i,j]

# Milk production ends at weaning; cow and calf are separated at weaning

if(MILKDAY[i+1,j] == WEANINGTIME+1) MILKDAY[i+1,j] <-0

# The number of calves born per reproductive cow is calculated from the number of

# conceptions

if(CALFNR[i,j] == 0) CALFLIVENR[i,j] <- 0 else CALFLIVENR[i,j] <- CALFNR[i-GestPer,j]

# The number of calves weaned per reproductive cow is calculated from the number of

# calves born.

if(CALFLIVENR[i,j] == 0) CALFWEANNR[i,j] <- 0 else

CALFWEANNR[i,j] <- CALFLIVENR[i-WEANINGTIME,j]

# Converts days in milk to weeks in milk (weeks)

MILKWEEK[i,j] = MILKDAY[i,j]/7

# Maximum milk production based on genotype (L day-1)

# This equation corresponds to Eq. 30 in the Supplementary Material

if(MILKWEEK[i,j] >0) MAXMILKPROD[i,j] <- MILKPARA\*MILKDAY[i,j]^MILKPARB\*

exp(-MILKPARC\*MILKDAY[i,j]) else MAXMILKPROD[i,j] <- 0

# Milk received by the calf from its mother (MJ ME day-1)

if(TIME[i,j] > WEANINGTIME) MEMILKCALFINIT[i,j] <- 0 else

MEMILKCALFINIT[i,j] <- MEMILKCALFINIT[i,j]

# Assumption: milk production is the maximum milk production based on the genotype

# (L day-1)

MILKPRODBF[i,j] = MAXMILKPROD[i,j]

# Energy balance

# Gross energy (GE, combustion value) in milk (MJ GE L-1)

GEMILK[i,j] =(((GEMILK1\*SENSMAT[94,s]) \*MILKDAY[i,j])+(GEMILK2\*SENSMAT[95,s]))/1000

# Maximum gross energy from milk production (MJ GE day-1)

GEMILKTOT[i,j] = GEMILK[i,j] \* MAXMILKPROD[i,j]

# Maximum metabolisable energy (ME) in milk (MJ ME day-1)

MEMILKCALF[i,j] = MILKDIG \* GEMILKTOT[i,j]

# Net energy (NE) requirement for milk production for reproductive cow (MJ NE day-1)

NEMILKCOW[i,j] = GEMILKTOT[i,j] / NEEFFMILK

# Heat generation for milk synthesis (MJ day-1)

HEATMILK[i,j] = NEMILKCOW[i,j] \* (1-NEEFFMILK)

# Protein balance

# Protein in milk (g protein day-1)

PROTMILK[i,j] <- MILKPRODBF[i,j] \* PROTFRACMILK \* 1000

# Gross amount of protein required for milk production (g protein day-1)

PROTMILKG[i,j] <- PROTMILK[i,j] / PROTEFFMILK

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# Growth #

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# Compensatory growth: potential growth can be exceeded. Assumption is that the

# compensatory growth isproportional to the difference between actual TBW and genetic

# potential TBW of the animal.

# Factor for compensatory growth for non carcass tissue (-)

COMPGROWTH1[i,j] <- min(COMPFACTTIS, max(1,NONCARCTIS[i,j]/NONCARCTISBF[i,j]))

# Factor for compensatory growth for bone tissue (-)

COMPGROWTH2[i,j] <- min(COMPFACTTIS, max(1,BONETIS[i,j]/BONETISBF[i,j]))

# Factor for compensatory growth for muscle tissue (-)

COMPGROWTH3[i,j] <- min(COMPFACTTIS, max(1,MUSCLETIS[i,j]/MUSCLETISBF[i,j]))

# Factor for compensatory growth for intramuscular fat tissue (-)

COMPGROWTH4[i,j] <- min(COMPFACTTIS, max(1,INTRAMFTIS[i,j]/INTRAMFTISBF[i,j]))

# Factor for compensatory growth for miscellaneous fat tissue (-)

COMPGROWTH5[i,j] <- min(COMPFACTTIS, max(1,MISCFATTIS[i,j]/MISCFATTISBF[i,j]))

# Weighted average of the factor for compensatory growth (-)

COMPGROWTH[i,j] <- COMPGROWTH1[i,j] \* (NONCARCTISBF[i,j]/(TBWBF[i,j]\*(1-RUMENFRAC))) +

COMPGROWTH2[i,j] \* (BONETISBF[i,j] /(TBWBF[i,j]\*(1-RUMENFRAC))) +

COMPGROWTH3[i,j] \* (MUSCLETISBF[i,j] /(TBWBF[i,j]\*(1-RUMENFRAC))) +

COMPGROWTH4[i,j] \* (INTRAMFTISBF[i,j]/(TBWBF[i,j]\*(1-RUMENFRAC))) +

COMPGROWTH5[i,j] \* (MISCFATTISBF[i,j]/(TBWBF[i,j]\*(1-RUMENFRAC)))

# Fraction lipid in the bone tissue (-)

LIPIDFRACBONEBF[i,j] = max((LIPBONE1\*SENSMAT[96,s]),((LIPBONE2\*SENSMAT[97,s])\*

log(BONETISBF[i,j]) + (LIPBONE3\*SENSMAT[98,s]))/100)

# Fraction lipid in the non-carcass tissue (-)

LIPIDFRACNONCBF[i,j] = ((LIPNONC1\*SENSMAT[99,s])\*NONCARCTISBF[i,j]^3 -

(LIPNONC2\*SENSMAT[100,s])\*NONCARCTISBF[i,j]^2 +

(LIPNONC3\*SENSMAT[101,s])\*NONCARCTISBF[i,j] -

(LIPNONC4\*SENSMAT[102,s]))/100 \*

(3.916E-10\* ((1-LIBRARY[21]-RUMENFRAC)\*LIBRARY[13])^4 -

7.058E-07\* ((1-LIBRARY[21]-RUMENFRAC)\*LIBRARY[13])^3 +

4.868E-04\* ((1-LIBRARY[21]-RUMENFRAC)\*LIBRARY[13])^2 -

1.593E-01\* ((1-LIBRARY[21]-RUMENFRAC)\*LIBRARY[13]) +

2.286E+01)

# Fraction protein in the non-carcass tissue

PROTFRACNONCBF[i,j] = ((PROTNONC1\*SENSMAT[103,s])\*NONCARCTISBF[i,j]^4 -

(PROTNONC2\*SENSMAT[104,s])\*NONCARCTISBF[i,j]^3 +

(PROTNONC3\*SENSMAT[105,s])\*NONCARCTISBF[i,j]^2 -

(PROTNONC4\*SENSMAT[106,s])\*NONCARCTISBF[i,j] +

(PROTNONC5\*SENSMAT[107,s]))/100

# Energy for growth, consists of three parts:

# 1. Genetic potential growth, including compensatory growth

# 2. Energy requirements to recover the depleted subcutaneous and intermuscular fat

# tissues

# 3. Reduction in energy for growth mentioned in 1 and 2 due to climatic conditions.

# Under energy limitation, tissues get energy according to their position in the

# hierarchy: 1. Non carcass tissue 2. Bone tissue 3. Muscle tissue 4. Intramuscular fat

# tissue 5. Subcutaneous and intermuscular fat tissue

# Factor to counter low weights of the miscellaneous and non-carcass tissues (-)

# This equation corresponds to Eq. 46 of the Supplementary Material

FATCOMP[i,j] <- max(0, FATTISCOMP-MISCFATTISBF[i,j]/MISCFATTIS[i,j])\*

(TBWBF[i,j]\*(1-RUMENFRAC))^0.75\*FATFACTOR

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# 2.3 Feed intake and digestion sub-model #

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# Digestion capacity limitation (related to the feed quality)

# Maximum digestion capacity (Fill Units per animal per day)

# This equation corresponds partly to Eq. 22 of the Supplementary Material

PHFEEDINT[i,j] = TBWBF[i,j]^0.75 \* PHFEEDCAP/1000 \*

max(0,min(1, ((RUMENDEV1\*SENSMAT[108,s]) \* TIME[i,j] -(RUMENDEV2\*SENSMAT[109,s]))))

# Code below enables to feed animal per 100 kg TBW (fixed % of the TBW)

if(FEEDNR[z] ==5) FEED1QNTY[i,j] <- FEED1QNTY[i,j] \* TBWBF[i,j]/100

if(FEEDNR[z] ==5) FEED2QNTY[i,j] <- FEED2QNTY[i,j] \* TBWBF[i,j]/100

# Feed intake cannot exceed the digestive capacity of the rumen

# Fill units feed type 1

FUFEED1[i,j] <- FEED1QNTY[i,j]\*FEED1[i,2]

# Maximum intake of feed type 1 based on the digestive capacity of the rumen (kg DM)

if((PHFEEDINT[i,j] - FUFEED1[i,j]) < 0) FEED1QNTYA[i,j] <- PHFEEDINT[i,j]/

(FEED1fr\*FEED1[i,2]+(1-FEED1fr)\*FEED2[i,2])\*FEED1fr else

FEED1QNTYA[i,j] <- FEED1QNTY[i,j]

# Fill units feed type 1 + feed type 2 (FU)

FUFEED2[i,j] <- FEED1QNTYA[i,j]\*FEED1[i,2] + FEED2QNTY[i,j]\*FEED2[i,2]

# Maximum intake of feed type 2 based on the digestive capacity of the rumen (kg DM)

if((PHFEEDINT[i,j] - FUFEED2[i,j]) < 0) FEED2QNTYA[i,j] <- PHFEEDINT[i,j]/

(FEED1fr\*FEED1[i,2]+(1-FEED1fr)\*FEED2[i,2])\*(1-FEED1fr) else

FEED2QNTYA[i,j] <- FEED2QNTY[i,j]

# Fill units feed type 1 + feed type 2 + feed type 3 (FU)

FUFEED3[i,j] <- FEED1QNTYA[i,j]\*FEED1[i,2] + FEED2QNTYA[i,j]\*FEED2[i,2] +

FEED3QNTY[i,j]\*FEED3[i,2]

# Maximum intake of feed type 3 based on the digestive capacity of the rumen (kg DM)

if((PHFEEDINT[i,j] - FUFEED3[i,j]) < 0)

FEED3QNTYA[i,j] <- max(0,(PHFEEDINT[i,j]-FUFEED2[i,j])/FEED3[i,2]) else

FEED3QNTYA[i,j] <- FEED3QNTY[i,j]

# Fill units feed type 1 + feed type 2 + feed type 3 + feed type 4 (FU)

FUFEED4[i,j] <- FEED1QNTY[i,j]\*FEED1[i,2] + FEED2QNTY[i,j]\*FEED2[i,2] +

FEED3QNTY[i,j]\*FEED3[i,2] + FEED4QNTY[i,j]\*FEED4[2]

# Maximum intake of feed type 4 based on the digestive capacity of the rumen (kg DM)

if((PHFEEDINT[i,j] - FUFEED4[i,j]) < 0)

FEED4QNTYA[i,j] <- max(0,(PHFEEDINT[i,j]-FUFEED3[i,j])/FEED4[2]) else

FEED4QNTY[i,j] <- FEED4QNTY[i,j]

FEED4QNTYA[i,j] <- min(FEED4QNTY[i,j], FEED4fr\*PHFEEDINT[i,j]/FEED4[2])

# Rumen fill classes according to Chilibroste et al. (1997)

if(FUFEED4[i,j] > PHFEEDINT[i,j]\* 0.85) PASSAGE[i,j] <- 1 else

if(FUFEED4[i,j] > PHFEEDINT[i,j]\* 0.65 & FUFEED4[i,j] < PHFEEDINT[i,j]\* 0.85)

PASSAGE[i,j] <- 2 else

if(FUFEED4[i,j] > PHFEEDINT[i,j]\* 0.45 & FUFEED4[i,j] < PHFEEDINT[i,j]\* 0.65)

PASSAGE[i,j] <- 3 else PASSAGE[i,j] <- 4

# Average crude protein (CP) in the diet (g CP)

CPAVG[i,j] <- (FEED1QNTYA[i,j]\*FEED1[i,16] + FEED2QNTYA[i,j]\*FEED2[i,16] +

FEED3QNTYA[i,j]\*FEED3[i,16] + FEED4QNTYA[i,j]\*FEED1[16]) /

(FEED1QNTYA[i,j] + FEED2QNTYA[i,j] + FEED3QNTYA[i,j] + FEED4QNTYA[i,j])

###########################################################################################

# 2.4 Integration thermoregulation, feed intake and digestion, and utilisation sub-models #

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# Initial four assumptions for the integration loop:

# 1. The reduction in NE availability due to heat stress is assumed to be zero

# (guesstimate, indicates absence of heatstress)

REDHP[i,j] <- 0

# 2. The increase in heat production due to cold stress is asssumed to be zero

# (guesstimate, indicates absence of cold stress)

HEATIFEEDGROWTHC[i,j] <- 0

# 3. The feed intake is 20 kg DM per animal per day. This number is generally too high

# for beef cattle, and this number is reduced later in the loop.

FEEDINTAKE[i,j] <- 20

# 4. The animal is assumed to be fed above the maintenance level

REDMAINT[i,j] <- 0

REPS[i,j] <- 0 # Indicates and counts the times the integration loop is repeated

repeat { # Start of the integration loop

# Minimum feed quantities based on rumen digestive capacity and the available feed

# quantity. Feed intake is reduced here from 20 kg DM head-1 day-1 to the correct

# amount

# Intake feed type 1 (kg DM per animal per day)

if(REPRODUCTIVE[j] == 1)

FEED1QNTY[i,j] <- max(0,min(FEED1QNTYA[i,j], FEED1fr\*FEEDINTAKE[i,j])) else

if(PRODUCTIVE[j] == 1 && SEX[j] == 0)

FEED1QNTY[i,j] <- max(0,min(FEED1QNTYA[i,j], FEED1fr\*FEEDINTAKE[i,j])) \* 1 else

if(PRODUCTIVE[j] == 1 && SEX[j] == 1)

FEED1QNTY[i,j] <- max(0,min(FEED1QNTYA[i,j], FEED1fr\*FEEDINTAKE[i,j])) \* 1 else

FEED1QNTY[i,j] <- max(0,min(FEED1QNTYA[i,j], FEED1fr\*FEEDINTAKE[i,j]))

# Intake feed type 2 (kg DM per animal per day)

if(REPRODUCTIVE[j] == 1)

FEED2QNTY[i,j] <- max(0,min(FEED2QNTYA[i,j], FEED2fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j])) else

if(PRODUCTIVE[j] == 1 && SEX[j] == 0)

FEED2QNTY[i,j] <- max(0,min(FEED2QNTYA[i,j], FEED2fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j])) \* 1 else

if(PRODUCTIVE[j] == 1 && SEX[j] == 1)

FEED2QNTY[i,j] <- max(0,min(FEED2QNTYA[i,j], FEED2fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j])) \* 1 else

FEED2QNTY[i,j] <- max(0,min(FEED2QNTYA[i,j], FEED2fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j]))

# Intake feed type 2 (kg DM per animal per day)

if(REPRODUCTIVE[j] == 1)

FEED3QNTY[i,j] <- max(0,min(FEED3QNTYA[i,j], FEED3fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j]-FEED2QNTY[i,j])) else

if(PRODUCTIVE[j] == 1 && SEX[j] == 0)

FEED3QNTY[i,j] <- max(0,min(FEED3QNTYA[i,j], FEED3fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j]-FEED2QNTY[i,j])) \* 1 else

if(PRODUCTIVE[j] == 1 && SEX[j] == 1)

FEED3QNTY[i,j] <- max(0,min(FEED3QNTYA[i,j], FEED3fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j]-FEED2QNTY[i,j])) \* 1 else

FEED3QNTY[i,j] <- max(0,min(FEED3QNTYA[i,j], FEED3fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j]-FEED2QNTY[i,j]))

if(REPRODUCTIVE[j] == 1)

FEED4QNTY[i,j] <- max(0,min(FEED4QNTYA[i,j], FEED4fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j]-

FEED2QNTY[i,j]-FEED3QNTY[i,j])) else

if(PRODUCTIVE[j] == 1 && SEX[j] == 0)

FEED4QNTY[i,j] <- max(0,min(FEED4QNTYA[i,j], FEED4fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j]-

FEED2QNTY[i,j]-FEED3QNTY[i,j])) else

if(PRODUCTIVE[j] == 1 && SEX[j] == 1)

FEED4QNTY[i,j] <- max(0,min(FEED4QNTYA[i,j], FEED4fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j]-

FEED2QNTY[i,j]-FEED3QNTY[i,j])) else

FEED4QNTY[i,j] <- max(0,min(FEED4QNTYA[i,j], FEED4fr\*FEEDINTAKE[i,j],

FEEDINTAKE[i,j]-FEED1QNTY[i,j]-

FEED2QNTY[i,j]-FEED3QNTY[i,j]))

# Total feed intake (kg DM per animal per day)

FEEDQNTY[i,j] <- FEED1QNTY[i,j] + FEED2QNTY[i,j] + FEED3QNTY[i,j] + FEED4QNTY[i,j]

# Crude protein content of the diet (g kg DM-1 feed)

if(FEEDQNTY[i,j] == 0) CPAVG[i,j] <- 0 else

CPAVG[i,j] <- (FEED1QNTY[i,j]\*FEED1[i,16] + FEED2QNTY[i,j]\*FEED2[i,16] +

FEED3QNTY[i,j]\*FEED3[i,16] + FEED4QNTY[i,j]\*FEED1[16]) /

FEEDQNTY[i,j]

# Calculates the fraction of each feed type in the diet

if(TIME[i,j] <= 14 | FEEDQNTY[i,j] == 0) FRACFEED1[i,j] <- 0 else

FRACFEED1[i,j] <- FEED1QNTY[i,j]/FEEDQNTY[i,j] # Fraction feed type 1 in diet

if(TIME[i,j] <= 14 | FEEDQNTY[i,j] == 0) FRACFEED2[i,j] <- 0 else

FRACFEED2[i,j] <- FEED2QNTY[i,j]/FEEDQNTY[i,j] # Fraction feed type 2 in diet

if(TIME[i,j] <= 14 | FEEDQNTY[i,j] == 0) FRACFEED3[i,j] <- 0 else

FRACFEED3[i,j] <- FEED3QNTY[i,j]/FEEDQNTY[i,j] # Fraction feed type 3 in diet

if(TIME[i,j] <= 14 | FEEDQNTY[i,j] == 0) FRACFEED4[i,j] <- 0 else

FRACFEED4[i,j] <- FEED4QNTY[i,j]/FEEDQNTY[i,j] # Fraction feed type 4 in diet

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# Feed intake and digestion sub-model (again) #

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# Maximum feed intake in kg, based on fill units (FU FU-1 kg)

PHFEEDINTKG[i,j] <- PHFEEDINT[i,j]/(FRACFEED1[i,j]\*FEED1[i,2]+

FRACFEED2[i,j]\*FEED2[i,2]+FRACFEED3[i,j]\*FEED3[i,2]+

FRACFEED4[i,j]\*FEED4[2])

# Digestion of carbohydrates

# INSC = insoluble, non-structural carbohydrates, which are assumed to mainly consist

# of starch)

# INSC digestion in the rumen (g INSC per animal per day)

INSC[i,j] <- FEED1QNTY[i,j] \* FEED1[i,4] \* FEED1[i,9] /

(FEED1[i,9] + FEED1[i,12]\*PASSRED[PASSAGE[i,j]]) +

FEED2QNTY[i,j] \* FEED2[i,4] \* FEED2[i,9] /

(FEED2[i,9] + FEED2[i,12]\*PASSRED[PASSAGE[i,j]]) +

FEED3QNTY[i,j] \* FEED3[i,4] \* FEED3[i,9] /

(FEED3[i,9] + FEED3[i,12]\*PASSRED[PASSAGE[i,j]]) +

FEED4QNTY[i,j] \* FEED4[4] \* FEED4[9] /

(FEED4[9] + FEED4[12]\*PASSRED[PASSAGE[i,j]])

# Total intake INSC in the feed (g INSC per animal per day)

INSCTOTAL[i,j] <- FEED1QNTY[i,j] \* FEED1[i,4] + FEED2QNTY[i,j] \* FEED2[i,4] +

FEED3QNTY[i,j] \* FEED3[i,4] + FEED4QNTY[i,j] \* FEED4[4]

# Fraction insoluble, non-structural carbohydrates digested in the rumen (-)

# (compare to Owens, 1986)

INSCDIG[i,j] <- INSC[i,j]/INSCTOTAL[i,j]

# Digestibility of INSC in the intestines is assumed to be 97% for all feeds

# (Moharrery et al, 2014)

INSCINT[i,j] <- max(0,(INSCTOTAL[i,j]\*TTDIGINSC)-INSC[i,j])

# Fraction INSC digested in the intestines (-)

INSCINTDIG[i,j] <- INSCINT[i,j]/INSCTOTAL[i,j]

# Digestion degradable neutral detergent fibre (NDF, g day-1)

NDF[i,j] <- FEED1QNTY[i,j] \* FEED1[i,5] \* FEED1[i,10] /

(FEED1[i,10] + FEED1[i,12]\*PASSRED[PASSAGE[i,j]]) +

FEED2QNTY[i,j] \* FEED2[i,5] \* FEED2[i,10] /

(FEED2[i,10] + FEED2[i,12]\*PASSRED[PASSAGE[i,j]]) +

FEED3QNTY[i,j] \* FEED3[i,5] \* FEED3[i,10] /

(FEED3[i,10] + FEED3[i,12]\*PASSRED[PASSAGE[i,j]]) +

FEED4QNTY[i,j] \* FEED4[5] \* FEED4[10] /

(FEED4[10] + FEED4[12]\*PASSRED[PASSAGE[i,j]])

# Total intake NDF (g day-1)

NDFTOTAL[i,j] <- FEED1QNTY[i,j] \* FEED1[i,5] + FEED2QNTY[i,j] \* FEED2[i,5] +

FEED3QNTY[i,j] \* FEED3[i,5] + FEED4QNTY[i,j] \* FEED4[5]

# Fraction degradable NDF digested in the rumen (-)

NDFDIG[i,j] <- NDF[i,j]/NDFTOTAL[i,j]

# NDF digestion in the intestines (g day-1)

# Cabral et al., 2011 (http://www.scielo.br/pdf/rbz/v40n9/a20v40n9.pdf)

# Volative fatty acids released are assumed not to be taken up by the animal

NDFINT[i,j] <- FEED1QNTY[i,j] \* FEED1[i,5] \* (1- FEED1[i,10] /

(FEED1[i,10] + FEED1[i,12]\*PASSRED[PASSAGE[i,j]])) \*

(FEED1[i,10]\*NDFDIGEST\*SENSMAT[110,s]) /

(FEED1[i,10]\*NDFDIGEST\*SENSMAT[110,s] + NDFPASS\*SENSMAT[111,s]) +

FEED2QNTY[i,j] \* FEED2[i,5] \* (1- FEED2[i,10] /

(FEED2[i,10] + FEED2[i,12]\*PASSRED[PASSAGE[i,j]])) \*

(FEED2[i,10]\*NDFDIGEST\*SENSMAT[110,s]) /

(FEED2[i,10]\*NDFDIGEST\*SENSMAT[110,s] + NDFPASS\*SENSMAT[111,s]) +

FEED3QNTY[i,j] \* FEED3[i,5] \* (1- FEED3[i,10] /

(FEED3[i,10] + FEED3[i,12]\*PASSRED[PASSAGE[i,j]])) \*

(FEED3[i,10]\*NDFDIGEST\*SENSMAT[110,s]) /

(FEED3[i,10]\*NDFDIGEST\*SENSMAT[110,s] + NDFPASS\*SENSMAT[111,s]) +

FEED4QNTY[i,j] \* FEED4[5] \* (1- FEED4[10] /

(FEED4[10] + FEED4[12]\*PASSRED[PASSAGE[i,j]]))\*

(FEED4[10]\*NDFDIGEST\*SENSMAT[110,s]) /

(FEED4[10]\*NDFDIGEST\*SENSMAT[110,s] + NDFPASS\*SENSMAT[111,s])

# Fraction degradable NDF digested in intestines (-)

NDFINTDIG[i,j] <- NDFINT[i,j]/NDFTOTAL[i,j]

# Fraction degradable NDF digested in intestines (g kg-1 DM feed)

NDFINTDIGTOT[i,j] <- NDFINT[i,j]/(FEEDQNTY[i,j]\*1000)

# Protein digestion

# Degradable crude protein (DCP) digestion in the rumen (g day-1)

PICP[i,j] <- FEED1QNTY[i,j] \* FEED1[i,7] \* FEED1[i,11] /

(FEED1[i,11] + FEED1[i,12]\*PASSRED[PASSAGE[i,j]]) +

FEED2QNTY[i,j] \* FEED2[i,7] \* FEED2[i,11] /

(FEED2[i,11] + FEED2[i,12]\*PASSRED[PASSAGE[i,j]]) +

FEED3QNTY[i,j] \* FEED3[i,7] \* FEED3[i,11] /

(FEED3[i,11] + FEED3[i,12]\*PASSRED[PASSAGE[i,j]]) +

FEED4QNTY[i,j] \* FEED4[7] \* FEED4[11] /

(FEED4[11] + FEED4[12]\*PASSRED[PASSAGE[i,j]])

# Total crude protein intake (g day-1)

PROTTOTAL[i,j] <- (FEED1QNTY[i,j] \* FEED1[i,16] + FEED2QNTY[i,j] \* FEED2[i,16] +

FEED3QNTY[i,j] \* FEED3[i,16] + FEED4QNTY[i,j] \* FEED4[16])

# Protein ending up in the intestines (g day-1)

PROTINT[i,j] <- PROTTOTAL[i,j] - (FEED1QNTY[i,j] \* FEED1[i,6] +

FEED2QNTY[i,j] \* FEED2[i,6] +

FEED3QNTY[i,j] \* FEED3[i,6] +

FEED4QNTY[i,j] \* FEED4[6]) - PICP[i,j]

# Lucas equation (g protein day-1), whole digestive tract, plus the effect of recycling

# This equation corresponds partly to Eq. 24 of the Supplementary Material and

# indicates the amount of protein taken up in the whole digestive tract.

PROTUPT[i,j] <- ((LUCAS1\*SENSMAT[112,s]) \* PROTTOTAL[i,j] -

(LUCAS2\*SENSMAT[113,s]) \* FEEDQNTY[i,j])

# Protein excreted (g protein day-1)

PROTEXCR[i,j] <- PROTTOTAL[i,j] - PROTUPT[i,j]

# Fraction protein digested in rumen (-)

PROTDIGRU[i,j] <- (PROTTOTAL[i,j]-PROTINT[i,j])/ PROTTOTAL[i,j]

# Fraction protein digested in the whole digestive tract (-)

PROTDIGWT[i,j] <- PROTUPT[i,j] / PROTTOTAL[i,j]

# Digestion and excretion

# Feed digested in the whole digestive tract (g day-1)

DIGFRAC[i,j] <- FEED1QNTY[i,j] \* (FEED1[i,3]+FEED1[i,6]) +

FEED2QNTY[i,j] \* (FEED2[i,3]+FEED2[i,6]) +

FEED3QNTY[i,j] \* (FEED3[i,3]+FEED3[i,6]) +

FEED4QNTY[i,j] \* (FEED4[3]+FEED4[6]) +

INSC[i,j] + INSCINT[i,j] + NDF[i,j] + NDFINT[i,j] + PROTUPT[i,j]

# Carbohydrates excreted (g day-1)

CHEXCR[i,j] <- FEEDQNTY[i,j]\*1000-DIGFRAC[i,j]-PROTEXCR[i,j]

# Manure dry matter excreted (g day-1)

EXCRFRAC[i,j] <- FEEDQNTY[i,j]\*1000-DIGFRAC[i,j]

# Gross energy (GE) content excreted dry matter (MJ GE kg-1 DM)

GEEXCR[i,j] <- (PROTEXCR[i,j] \* GEPROT + CHEXCR[i,j] \* GECARB) /

(PROTEXCR[i,j] + CHEXCR[i,j])

# GE content digested feed (MJ GE kg-1 DM)

# This equation is similar to Eq. 25 in the Supplementary Material

GEUPTAKE[i,j] <- (PROTUPT[i,j] \* GEPROT + (DIGFRAC[i,j]-PROTUPT[i,j]) \* GECARB) /

(DIGFRAC[i,j])

# ME uptake (MJ ME day-1); 0.82 is conversion DE --> ME

if(EXCRFRAC[i,j] == 0) MEUPTAKE[i,j] <-0 else MEUPTAKE[i,j] <- DIGFRAC[i,j]/1000

\* GEUPTAKE[i,j] \* DETOME

# Digestibility feed (g g-1), on an energy basis

if(EXCRFRAC[i,j] == 0) Q[i,j] <-0 else Q[i,j] = DIGFRAC[i,j]/(FEEDQNTY[i,j]\*1000)

\* (GEUPTAKE[i,j] /GEFEED)

# Average heat increment of feeding (MJ MJ-1)

if((FEED1QNTY[i,j] + FEED2QNTY[i,j] + FEED3QNTY[i,j] + FEED4QNTY[i,j]) == 0)

Digestfracfeed[i,j] <- 0.3 else

Digestfracfeed[i,j] <- (FEED1QNTY[i,j] \* FEED1[i,1] + FEED2QNTY[i,j] \* FEED2[i,1] +

FEED3QNTY[i,j] \* FEED3[i,1] + FEED4QNTY[i,j] \* FEED4[1])/

(FEED1QNTY[i,j] + FEED2QNTY[i,j] + FEED3QNTY[i,j] + FEED4QNTY[i,j])

# If feed intake is not reduced, no energy requirement for respiration above

# maintenance

# Increase in net energy (NE) requirements due to heat stress (MJ NE day-1)

if(REDHP[i,j] == 0) NERESPC[i,j] <- 0 else NERESPC[i,j] <- NERESP[i,j]/1000

# Increase in protein requirements under maximum heat release and heat stress (g day-1)

PROTRESP[i,j] <- NERESPC[i,j] \* PROTNE \* NtoCP

#######################################################################################

# Milk for the calf from the cow until weaning (MJ GE day-1)

if(TIME[i,j]<=WEANINGTIME)

MILKSTART[i,j] <- LIBRARY[15]\*TIME[i,j]^MILKPARB\*exp(-MILKPARC\*TIME[i,j]) \*

(((GEMILK1\*TIME[i,j])+2771)/1000) \* MILKDIG else MILKSTART[i,j] <- 0

# Digested protein from milk for the calf (g day-1)

# 95% protein digestibility; 3.5% protein in milk, heat increment of feeding taken into

# account

if(TIME[i,j]<=WEANINGTIME)

MILKSTARTPR[i,j] <- LIBRARY[15]\*TIME[i,j]^MILKPARB\*exp(-MILKPARC\*TIME[i,j]) \* 35 \*

MILKDIG else MILKSTARTPR[i,j] <- 0

MILKSTARTPRHF[i,j] <- MILKSTARTPR[i,j] \* (1+(Digestfracfeed[i,j]/(1-Digestfracfeed[i,j])))

# Milk from reproductive cow for calf (MJ ME day-1)

MEMILKCALFINIT[i,j] <- MILKSTART[i,j] \*

(1+(Digestfracfeed[i,j]/(1-Digestfracfeed[i,j])))

# Protein for non-growth purposes

# Total fixed protein requirements (g protein day-1)

PROTNONG[i,j] <- PROTDERML[i,j] + PROTMAINT[i,j] + PROTPHACT[i,j] + PROTGESTG[i,j] +

PROTMILKG[i,j] + PROTRESP[i,j]

# Heat increment of feeding (MJ day-1)

HIFM[i,j] <- (NEMAINT[i,j]/1000+NEPHYSACT[i,j]/1000+NEREQGEST[i,j]+

NEMILKCOW[i,j]+NERESPC[i,j]/1000) \*

(Digestfracfeed[i,j]/(1-Digestfracfeed[i,j]))

# Protein requirements for fixed processes, i.e. excluding growth (g protein day-1)

PROTNONGM[i,j] <- PROTNONG[i,j] + HIFM[i,j] \* PROTNE \* NtoCP

# Energy not invested in growth is converted into heat (MJ day-1)

HEATIFEEDMAINT[i,j] = NEMAINT[i,j]/1000 + NEPHYSACT[i,j]/1000 + HEATGEST[i,j] +

HEATMILK[i,j] + NERESPC[i,j]/1000 + HIFM[i,j] + HEATIFEEDGROWTHC[i,j]/DISSEFF +

REDMAINT[i,j]

# Sum of all heat released that is not related to growth, includes heat increment of

# feeding (MJ day-1)

HEATIFEEDMAINTWM[i,j] = HEATIFEEDMAINT[i,j]/(3600\*24\* AREA[i,j])\*1000000

# Heat release under maintenance level is not taken into account yet.

# Maximum heat release from growth (W m-2)

HEATIFEEDGROWTHWM[i,j] = Metheatopt[i,j]-HEATIFEEDMAINTWM[i,j]

# Maximum heat release from growth (MJ day-1)

HEATIFEEDGROWTH[i,j] = HEATIFEEDGROWTHWM[i,j]\*(3600\*24\* AREA[i,j])/1000000

# Superfluous heat produced under sub-maintenance level is taken into account here

# (MJ day-1)

if(HEATIFEEDGROWTH[i,j] < 0) REDMAINT[i,j] <- HEATIFEEDGROWTH[i,j] else

REDMAINT[i,j] <- 0

# Energy available for growth, after accounting for heat increment of feeding (MJ NE

# day-1)

ENFEEDGROWTHQ[i+1,j] <- ((MEUPTAKE[i,j]) - HEATIFEEDMAINT[i,j] + MEMILKCALFINIT[i,j]) /

(1+(Digestfracfeed[i,j]/(1-Digestfracfeed[i,j])))

ENFEEDGROWTHQ[i+1,j] <- ENFEEDGROWTHQ[i+1,j] - 0.134\*NEREQGEST[i,j] -

(NEMILKCOW[i,j]-HEATMILK[i,j])

# Integrates the net energy for growth, based on the genetic potential (ENGRTOTAL),

# the climate (REDHP), and feed-limitation (ENFEEDGROWTHQ)

# Energy available for growth (MJ NE day-1)

ENFEEDGROWTH[i+1,j] = min(ENFEEDGROWTHQ[i+1,j], ENGRTOTAL[i+1,j] \* COMPGROWTH[i,j]) +

REDHP[i,j]

# Fraction NE for growth allocated to the non-carcass tissue (-)

FRENGRNONCBF[i+1,j] = max(0,(ENFEEDGROWTH[i+1,j]-FATCOMP[i,j])/ENFEEDGROWTH[i+1,j])

if(NONCARCTISBF[i,j]/NONCARCTIS[i,j] < 1)

FRENGRNONCBF[i+1,j] <- FRENGRNONCBF[i+1,j] else FRENGRNONCBF[i+1,j] <- 0

# NE for growth allocated to the non-carcass tissue (MJ day-1)

ENGRNONCBF[i+1,j] = FRENGRNONCBF[i+1,j]\* (ENGRNONC[i+1,j]/ENGRTOTALORIG[i+1,j]) \*

(ENFEEDGROWTH[i+1,j]) \* COMPGROWTH1[i,j] \* ((TBWBF[i,j]/LIBRARY[13])\*-

(ENNONC1\*SENSMAT[114,s]-ENNONC2\*SENSMAT[115,s])+ENNONC1\*SENSMAT[114,s])/

(ENGRNONC[i+1,j]/ENGRTOTALORIG[i+1,j])

ENGRNONCBF[i+1,j] = max(ENGRNONCBF[i+1,j],0) # NE for growth cannot be negative

# Fraction NE for growth allocated to the bone tissue (-)

FRENGRBONEBF[i+1,j] = max(0,(ENFEEDGROWTH[i+1,j]-FATCOMP[i,j])/(ENFEEDGROWTH[i+1,j]))

if(BONETISBF[i,j]/BONETIS[i,j] < 1)

FRENGRBONEBF[i+1,j] <- FRENGRBONEBF[i+1,j] else FRENGRBONEBF[i+1,j] <- 0

# NE for growth allocated to the bone tissue (MJ day-1)

ENGRBONEBF[i+1,j] = FRENGRBONEBF[i+1,j]\* (ENGRBONE[i+1,j]/ENGRTOTALORIG[i+1,j]) \*

(ENFEEDGROWTH[i+1,j]) \* COMPGROWTH2[i,j]

ENGRBONEBF[i+1,j] = max(ENGRBONEBF[i+1,j],0) # NE for growth cannot be negative

# Fraction NE for growth allocated to the muscle tissue (-)

FRENGRMUSCLEBF[i+1,j] = max(0,(ENFEEDGROWTH[i+1,j]-FATCOMP[i,j])/(ENFEEDGROWTH[i+1,j]))

if(MUSCLETISBF[i,j]/MUSCLETIS[i,j] < 1)

FRENGRMUSCLEBF[i+1,j] <- FRENGRMUSCLEBF[i+1,j] else FRENGRMUSCLEBF[i+1,j] <- 0

# NE for growth allocated to the muscle tissue (MJ day-1)

ENGRMUSCLEBF[i+1,j] = FRENGRMUSCLEBF[i+1,j]\* (ENGRMUSCLE[i+1,j]/

ENGRTOTALORIG[i+1,j]) \* (ENFEEDGROWTH[i+1,j]) \*

COMPGROWTH3[i,j]

ENGRMUSCLEBF[i+1,j] = max(ENGRMUSCLEBF[i+1,j],0) # NE for growth cannot be negative

# Fraction NE for growth allocated to the intramuscular fat tissue (-)

FRENGRIMFBF[i+1,j] = max(0,(ENFEEDGROWTH[i+1,j]-FATCOMP[i,j])/(ENFEEDGROWTH[i+1,j]))

if(INTRAMFTISBF[i,j]/INTRAMFTIS[i,j] < 1)

FRENGRIMFBF[i+1,j] <- FRENGRIMFBF[i+1,j] else FRENGRIMFBF[i+1,j] <- 0

# NE for growth allocated to the intramuscular fat tissue (MJ day-1)

ENGRIMFBF[i+1,j] = FRENGRIMFBF[i+1,j]\* (ENGRIMF[i+1,j]/ENGRTOTALORIG[i+1,j]) \*

(ENFEEDGROWTH[i+1,j]) \* COMPGROWTH4[i,j]

ENGRIMFBF[i+1,j] = max(ENGRIMFBF[i+1,j],0) # NE for growth cannot be negative

# NE for growth allocated to the miscellaneous fat tissue (MJ day-1); balancing

# variable

ENGRFATBF[i+1,j] = ENFEEDGROWTH[i+1,j]-ENGRNONCBF[i+1,j]-ENGRBONEBF[i+1,j]-

ENGRMUSCLEBF[i+1,j]-ENGRIMFBF[i+1,j]

ENGRFATBF[i+1,j] = max(ENGRFATBF[i+1,j],0) # NE for growth cannot be negative

# Check on NE for growth (MJ day-1); positive values CHECKCOMP are wrong

ENGRTOTALCOMP[i+1,j] = ENGRNONCBF[i+1,j] + ENGRBONEBF[i+1,j] +

ENGRMUSCLEBF[i+1,j] + ENGRIMFBF[i+1,j] + ENGRFATBF[i+1,j]

CHECKCOMP[i+1,j] = ENFEEDGROWTH[i+1,j] - ENGRTOTALCOMP[i+1,j]

# Heat production actual growth (13.9 MJ kg-1 for lipid, and 20.2 MJ kg-1 for protein)

# Heat production related to growth of bone tissue (MJ day-1)

HEATBONEACT[i,j] = DERBONE[i,j] \* ENGRBONEBF[i+1,j]/ENGRBONE[i+1,j] \*

(LIPIDFRACBONEBF[i,j] \* (GELIPID/LIPIDEFF-GELIPID) + PROTFRACBONE \*

(GEPROT/PROTEFF-GEPROT))

# Heat production related to growth of muscle tissue (MJ day-1)

HEATMUSCLEACT[i,j] = DERMUSCLE[i,j] \* ENGRMUSCLEBF[i+1,j]/ENGRMUSCLE[i+1,j] \*

(LIPFRACMUSCLE \* (GELIPID/LIPIDEFF-GELIPID) + PROTFRACMUSCLE \*

(GEPROT/PROTEFF-GEPROT))

# Heat production related to growth of intramuscular fat tissue (MJ day-1)

HEATIMFACT[i,j] = DERINTRAMF[i,j] \* ENGRIMFBF[i+1,j]/ENGRIMF[i+1,j] \*

(LIPFRACFAT \* (GELIPID/LIPIDEFF-GELIPID) + PROTFRACFAT \* (GEPROT/PROTEFF-GEPROT))

# Heat production related to growth of miscellaneous fat tissue (MJ day-1)

HEATMISCFATACT[i,j] = DERMISCFAT[i,j] \* ENGRFATBF[i+1,j]/ENGRFAT[i+1,j] \*

(LIPFRACFAT \* (GELIPID/LIPIDEFF-GELIPID) + PROTFRACFAT \* (GEPROT/PROTEFF-GEPROT))

# Heat production related to growth of non-carcass tissue (MJ day-1)

HEATNONCACT[i,j] = DERNONC[i,j] \* ENGRNONCBF[i+1,j]/ENGRNONC[i+1,j] \*

(LIPIDFRACNONCBF[i,j] \* (GELIPID/LIPIDEFF-GELIPID) + PROTFRACNONCBF[i,j] \*

(GEPROT/PROTEFF-GEPROT))

# Total heat production related to NE for growth (MJ day-1)

HEATTOTALACT[i,j] = HEATBONEACT[i,j] + HEATMUSCLEACT[i,j] + HEATIMFACT[i,j] +

HEATMISCFATACT[i,j] + HEATNONCACT[i,j]

# Net energy (NE) requirements for growth (MJ day-1)

# 44.0 MJ kg-1 for protein, 53.7 MJ kg-1 for lipid

# NE requirements for growth of the bone tissue (MJ day-1)

ENBONEACT[i,j] = DERBONE[i,j] \* ENGRBONEBF[i+1,j]/ENGRBONE[i+1,j] \*

(LIPIDFRACBONEBF[i,j] \* GELIPID/LIPIDEFF + PROTFRACBONE \* GEPROT/PROTEFF)

# NE requirements for growth of the muscle tissue (MJ day-1)

ENMUSCLEACT[i,j] = DERMUSCLE[i,j] \* ENGRMUSCLEBF[i+1,j]/ENGRMUSCLE[i+1,j] \*

(LIPFRACMUSCLE \* GELIPID/LIPIDEFF + PROTFRACMUSCLE \* GEPROT/PROTEFF)

# NE requirements for growth of the intramuscular fat tissue (MJ day-1)

ENIMFACT[i,j] = DERINTRAMF[i,j] \* ENGRIMFBF[i+1,j]/ENGRIMF[i+1,j] \*

(LIPFRACFAT \* GELIPID/LIPIDEFF + PROTFRACFAT \* GEPROT/PROTEFF)

# NE requirements for growth of the miscellaneous fat tissue (MJ day-1)

ENMISCFATACT[i,j] = DERMISCFAT[i,j] \* ENGRFATBF[i+1,j]/ENGRFAT[i+1,j] \*

(LIPFRACFAT \* GELIPID/LIPIDEFF + PROTFRACFAT \* GEPROT/PROTEFF)

# NE requirements for growth of the non-carcass tissue (MJ day-1)

ENNONCACT[i,j] = DERNONC[i,j] \* ENGRNONCBF[i+1,j]/ENGRNONC[i+1,j] \*

(LIPIDFRACNONCBF[i,j] \* GELIPID/LIPIDEFF + PROTFRACNONCBF[i,j] \* GEPROT/PROTEFF)

# Total NE requirements for growth of all tissues (MJ day-1)

ENTOTALACT[i,j] = ENBONEACT[i,j] + ENMUSCLEACT[i,j] + ENIMFACT[i,j] +

ENMISCFATACT[i,j] + ENNONCACT[i,j]

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# Protein requirements for growth

# Protein use efficiency for growth is assumed to be 54% (23.8/44.0 = 0.54)

# Protein requirement for growth of bone tissue (g day-1)

PROTBONEACT[i,j] = DERBONE[i,j] \* ENGRBONEBF[i+1,j]/ENGRBONE[i+1,j] \*

PROTFRACBONE / PROTEFF \* 1000

# Protein requirement for growth of muscle tissue (g day-1)

PROTMUSCLEACT[i,j] = DERMUSCLE[i,j] \* ENGRMUSCLEBF[i+1,j]/ENGRMUSCLE[i+1,j] \*

PROTFRACMUSCLE / PROTEFF \* 1000

# Protein requirement for growth of intramuscular fat tissue (g day-1)

PROTIMFACT[i,j] = DERINTRAMF[i,j] \* ENGRIMFBF[i+1,j]/ENGRIMF[i+1,j] \*

PROTFRACFAT / PROTEFF \* 1000

# Protein requirement for growth of intermuscular and subcutaneous fat tissue (g day-1)

PROTMISCFATACT[i,j] = DERMISCFAT[i,j] \* ENGRFATBF[i+1,j]/ENGRFAT[i+1,j] \*

PROTFRACFAT / PROTEFF \* 1000

# Protein requirement for growth of non-carcass tissue (g day-1)

PROTNONCBF1[i,j] = DERNONC[i,j] \* ENGRNONCBF[i+1,j]/ENGRNONC[i+1,j] \*

PROTFRACNONCBF[i,j] / PROTEFF \* 1000

# Total protein requirements for growth (g protein day-1)

PROTTOTALACT[i,j] = PROTBONEACT[i,j] + PROTMUSCLEACT[i,j] + PROTIMFACT[i,j] +

PROTMISCFATACT[i,j] + PROTNONCBF1[i,j]

# Total protein requirement (g protein day-1), excluding recycling of protein

PROTGROSS[i,j] <- PROTNONGM[i,j] + PROTTOTALACT[i,j] +

ENTOTALACT[i,j]\*(Digestfracfeed[i,j]/(1-Digestfracfeed[i,j])) \* PROTNE \* NtoCP +

HEATTOTALACT[i,j] \* PROTNE \* NtoCP

# Digested protein not accreted in tissues (g day-1)

UREABL[i,j] <- PROTGROSS[i,j] - PROTDERML[i,j] + PROTEFF\*PROTTOTALACT[i,j] +

0.85\*PROTGESTG[i,j] + PROTEFFMILK\*PROTMILKG[i,j]

# Percentage of urea N recycled, percentage from N intake (%) (Russel et al, 1992)

NRECYCLPT[i,j] <- NRECYCL1\*SENSMAT[116,s] - NRECYCL2\*SENSMAT[117,s]\*(CPAVG[i,j]/10) +

NRECYCL3\*SENSMAT[118,s]\*(CPAVG[i,j]/10)^2

if(TIME[i,j]<=14) NRECYCLPT[i,j] <- 0 # No recycling when only milk is supplied

# Net protein requirement (g protein day-1), including recycling

PROTNETT[i,j] <- PROTGROSS[i,j] - (NRECYCLPT[i,j]/100) \* (CPAVG[i,j] \* FEEDQNTY[i,j])

# Additional energy requirements under cold stress (MJ day-1)

HEATIFEEDGROWTHC[i,j] <- HEATIFEEDGROWTHC[i,j] + max(0,(Metheatcold[i,j]-

HEATIFEEDMAINTWM[i,j])\*(3600\*24\* AREA[i,j])/1000000 -

HEATTOTALACT[i,j] - ENTOTALACT[i,j]\*

(Digestfracfeed[i,j]/(1-Digestfracfeed[i,j])))

#########################################################################################

# ME to feed conversion #

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# Metabolisable energy (ME) requirements (MJ per animal per day)

# Only for feed, energy for calf (MEMILKCALFINIT) is subtracted

# The 0.134 can be defined more precisely: (1-NEIEFFGEST)\*(45/75)

MEREQTOTAL[i,j] = max(0,HEATIFEEDMAINT[i,j]-MEMILKCALFINIT[i,j]+(ENFEEDGROWTH[i+1,j]+

(0.134)\*NEREQGEST[i,j]+(NEMILKCOW[i,j]-HEATMILK[i,j]))\*

(1+(Digestfracfeed[i,j]/(1-Digestfracfeed[i,j])))

+ REDMAINT[i,j]/(Digestfracfeed[i,j]-0.10)\*

(1-(Digestfracfeed[i,j]-0.10)))

# Metabolisable energy (ME) requirements (MJ per day)

MEMET[i,j] <- HEATIFEEDMAINT[i,j]-MEMILKCALFINIT[i,j]+(ENFEEDGROWTH[i+1,j]+0.134\*

NEREQGEST[i,j]+(NEMILKCOW[i,j]-HEATMILK[i,j]))\*(1+(Digestfracfeed[i,j]/

(1-Digestfracfeed[i,j])))

# Reduction in ME (MJ per day)

MERED[i,j] <- REDMAINT[i,j]/(Digestfracfeed[i,j]-0.10)\*(1-(Digestfracfeed[i,j]-0.10))

# Feed intake (kg DM per day)

if(MEUPTAKE[i,j] == 0) FEEDINTAKE[i,j] <- 0 else

FEEDINTAKE[i,j] <- (MEREQTOTAL[i,j] / (Q[i,j]\*GEFEED))/DETOME

# Fraction of the digestion capacity used (-)

if(MEUPTAKE[i,j] == 0) FILLGIT[i,j] <- 0 else

FILLGIT[i,j] <- FEEDQNTY[i,j] / PHFEEDINTKG[i,j]

# Rumen/ digestion capacity classes as defined by Chilibroste et al. (1997)

if(FILLGIT[i,j] > 0.85) PASSAGE1[i,j] <- 1 else

if(FILLGIT[i,j] <= 0.85 & FILLGIT[i,j] > 0.65) PASSAGE1[i,j] <- 2 else

if(FILLGIT[i,j] <= 0.65 & FILLGIT[i,j] > 0.45) PASSAGE1[i,j] <- 3 else

PASSAGE1[i,j] <- 4

# Possible difference in digestion capacity class after calculation of FILLGIT

PASSDIFF[i,j] <- max(0,PASSAGE1[i,j]-PASSAGE[i,j])

if(TIME[i,j] > 15) PASSAGE[i,j] <- PASSAGE[i,j] + PASSDIFF[i,j]

REPS[i,j] <- REPS[i,j] + 1 # Times the integration loop has run

# Optimization statement in the integration loop (among the different sub-models)

PROTBAL[i,j] <- PROTUPT[i,j]\* (1+NRECYCLPT[i,j]/100) +

MILKSTARTPRHF[i,j] - PROTGROSS[i,j]

PROTREDFACT[i,j] <- 1- min(1,max(0,((PROTBAL[i,j]\*-1)/(PROTGROSS[i,j]-PROTNONGM[i,j]))))

# This statement indicates that heat production from growth (HEATTOTALACT plus HIF for

# ENTOTALACT) cannot exceed the maximum heat release (HEATIFEEDGROWTH) by more than 0.5

# MJ day-1

DIFFEN[i,j] = HEATTOTALACT[i,j]+ENTOTALACT[i,j]\*(Digestfracfeed[i,j]/

(1-Digestfracfeed[i,j])) - max(0,HEATIFEEDGROWTH[i,j])

# If heat production exceeds the maximum heat release, feed intake is reduced via REDHP.

# REDHP accounts for heat stress

if(DIFFEN[i,j] > 0.5) REDHP[i,j] <- (REDHP[i,j]-0.1\*DIFFEN[i,j]) else

REDHP[i,j] <- REDHP[i,j]

# If the passage rate is not correct, the integration loop does not change passage rate

# and feed intake at the same time

if(TIME[i,j] > 15 & PASSDIFF[i,j] != 0) REDHP[i,j] <- 0

# The loop has to run at least two times

if(REPS[i,j] < 2) CHECKHEAT3[i,j] <- "FALSE" else CHECKHEAT3[i,j] <- "CORRECT"

# Passage rate has to be correct before the loop terminates

if(TIME[i,j] > 15 && PASSDIFF[i,j] != 0) CHECKHEAT3[i,j] <- "FALSE"

# Heat production cannot exceed maximum heat release before the loop terminates

if(DIFFEN[i,j] > 0.5) CHECKHEAT3[i,j] <- "FALSE"

# If all conditions are met, the integration loop terminates

if(CHECKHEAT3[i,j] == "CORRECT") {break}

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} # End of the integration loop

# Fraction physically effective neutral detergent fibre (peNDF) in the diet (-)

# Note: diets must contain sufficient peNDF to avoid unrealistic simulations where rumen

# functioning cannot be sustained.

PENDF[i,j] <- FRACFEED1[i,j]\*FEED1[i,14]\*FEED1[i,15] +

FRACFEED2[i,j]\*FEED2[i,14]\*FEED2[i,15] +

FRACFEED3[i,j]\*FEED3[i,14]\*FEED3[i,15] +

FRACFEED4[i,j]\*FEED4[14]\*FEED4[15]

# Tissue weights are corrected for protein deficiency (PROTREDFACT)

# Weight of lipids in bone tissue (kg per animal)

LIPIDBONEBF[i+1,j] = LIPIDBONEBF[i,j] + DERBONE[i,j]\* ENGRBONEBF[i+1,j]/

ENGRBONE[i+1,j] \* LIPIDFRACBONEBF[i,j] \* PROTREDFACT[i,j]

# Weight of lipids in the non-carcass tissue (kg per animal)

LIPIDNONCBF[i+1,j] = LIPIDNONCBF[i,j] + DERNONC[i,j]\* ENGRNONCBF[i+1,j]/

ENGRNONC[i+1,j] \* LIPIDFRACNONCBF[i,j] \* PROTREDFACT[i,j]

# Weight of protein in the non-carcass tissue (kg per animal)

PROTNONCBF[i+1,j] = PROTNONCBF[i,j] + DERNONC[i,j]\* ENGRNONCBF[i+1,j]/

ENGRNONC[i+1,j] \* PROTFRACNONCBF[i,j] \* PROTREDFACT[i,j]

# Bone tissue (kg per animal)

BONETISBF[i+1,j] = BONETISBF[i,j] + DERBONE[i,j] \*

ENGRBONEBF[i+1,j]/ENGRBONE[i+1,j] \* PROTREDFACT[i,j]

# Muscle tissue (kg per animal)

MUSCLETISBF[i+1,j] = MUSCLETISBF[i,j] + DERMUSCLE[i,j] \*

ENGRMUSCLEBF[i+1,j]/ENGRMUSCLE[i+1,j] \* PROTREDFACT[i,j]

# Intramuscular fat tissue (kg per animal)

INTRAMFTISBF[i+1,j] = INTRAMFTISBF[i,j] + DERINTRAMF[i,j] \*

ENGRIMFBF[i+1,j]/ENGRIMF[i+1,j] \* PROTREDFACT[i,j]

# Subcutaneous and intermuscular fat tissue (kg per animal)

MISCFATTISBF[i+1,j] = MISCFATTISBF[i,j] + DERMISCFAT[i,j] \*

ENGRFATBF[i+1,j]/ENGRFAT[i+1,j] \* PROTREDFACT[i,j]

# Non-carcass tissue (kg per animal)

NONCARCTISBF[i+1,j] = NONCARCTISBF[i,j] + DERNONC[i,j] \*

ENGRNONCBF[i+1,j]/ENGRNONC[i+1,j] \* PROTREDFACT[i,j]

# Gross energy content of the non-carcass tissue (MJ kg-1)

ENCONTENTNONCBF[i,j] = (LIPIDNONCBF[i,j] \* GELIPID + PROTNONCBF[i,j] \* GEPROT) /

NONCARCTISBF[i,j]

# Muscle tissue is dissimilated when protein supply is below maintenance

# Protein dissimilation: efficiency of 90% assumed

# Reduction in muscle tissue (kg day-1)

REDTISPROT[i,j] <- min(0, PROTGROSS[i,j]+PROTBAL[i,j]) /

(PROTFRACMUSCLE\* DISSEFF \* 1000)

MUSCLETISBF[i+1,j] <- MUSCLETISBF[i+1,j] + REDTISPROT[i,j]

# REDTIS1 Heat stress: reduction in feed intake heat release in under sub-maintenance

# intake

# Weight loss due to heat stress, in (kg fat per day), 29.624 MJ kg-1 is the

# energy content of fat tissue

# inefficiency fat dissimilation = 10%; i.e. 90% efficiency

REDTIS[i,j] = REDMAINT[i,j]/(Digestfracfeed[i,j]-(1-DISSEFF))\*

(1-(Digestfracfeed[i,j]-(1-DISSEFF)))/GEFATTIS

REDTIS[is.nan(REDTIS)] <- 0

# Fat tissue (cumulative energy) dissimulated due to heat stress (MJ)

HEATBURNCUMUL[i,j] = sum(REDTIS[1:i,j])\*GEFATTIS

# To avoid heat stress, subcutaneous and intermuscular fat are dissimilated (kg day-1)

# (and feed intake is reduced)

MISCFATTISBF[i+1,j] <- MISCFATTISBF[i+1,j] + REDTIS[i,j] \* 0.9

# To avoid heat stress, non carcass tissue is dissimilated (kg day-1)

NONCARCTISBF[i+1,j] <- NONCARCTISBF[i+1,j] + REDTIS[i,j] \* 0.1 \*

(GEFATTIS/ENCONTENTNONCBF[i,j])/DISSEFF

# Check to ensure feed intake is not negative

if((NEMAINT[i,j]+NEPHYSACT[i,j]+NERESP[i,j])\*1/DISSEFF < -1\*REDTIS[i,j])

CHECK[i,j] <- "wrong" else CHECK[i,j] <-"good"

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# REDTIS2 Negative growth, fat tissue is dissimilated (kg day-1)

# This equation is similar to Eq. 47 of the Supplementary Material

if(REDTIS[i,j] == 0 && ENFEEDGROWTH[i+1,j] < 0)

REDTIS2[i,j] <- (-ENFEEDGROWTH[i+1,j]/GEFATTIS)/DISSEFF else REDTIS2[i,j] <- 0

# To correct for negative growth, subcutaneous and intermuscular fat tissue are

# dissimilated (kg day-1)

MISCFATTISBF[i+1,j] <- MISCFATTISBF[i+1,j] - REDTIS2[i,j] \* 0.9

NONCARCTISBF[i+1,j] <- NONCARCTISBF[i+1,j] - REDTIS2[i,j] \* 0.1 \*

(GEFATTIS/ENCONTENTNONCBF[i,j])/DISSEFF

# REDTIS3 Cold stress

# Cumulative energy required to maintain body temperature (MJ)

FATBURNCUMUL[i+1,j] = FATBURNCUMUL[i,j] + HEATIFEEDGROWTHC[i,j]

# Total body weight (TBW) based on the genotype, climate (heat stress; cold stress), feed

# quality, and available feed quantity (kg live weight)

TBWBF[i+1,j] = (BONETISBF[i+1,j] + MUSCLETISBF[i+1,j] + INTRAMFTISBF[i+1,j] +

MISCFATTISBF[i+1,j] + NONCARCTISBF[i+1,j])/(1-RUMENFRAC)

# Metabolic body weight (TBW) based on the genotype, climate (heat stress; cold stress),

# feed quality, and available feed quantity (kg live weight)

EBWBFMET[i+1,j] <- (TBWBF[i+1,j]\*(1-RUMENFRAC))^0.75

# Protein accretion in body tissues and milk (g day-1)

PROTACCR[i,j] <- PROTGESTG[i,j]\*0.5 + PROTMILK[i,j] + PROTTOTALACT[i,j]

# Fraction metabolisable energy from feed used for maintenance (-)

MAINTFRAC[i,j] = (HEATIFEEDMAINT[i,j]-HEATIFEEDGROWTHC[i,j]+MEMILKCALFINIT[i,j])/

MEREQTOTAL[i,j]

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# Culling and slaughtering cattle #

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# Cattle slaughtered (cattle from reproductive herd)

FATFRACCARC[i,j] = (MISCFATTISBF[i,j]+INTRAMFTISBF[i,j])/(MISCFATTISBF[i,j]+

INTRAMFTISBF[i,j]+MUSCLETISBF[i,j]+BONETISBF[i,j])

# Maximum number of calves per animal

CALVESPERANIMAL <- REPRODUCTIVE \* MAXCALFNR

# Beef production (kg per animal)

# (Beef is deboned carcass)

# Option 1: fat content reaches a specific level for cows, and CALFLIVENR should be met

# for cows. This equation contains Eq. 38 of the Supplementary Material

if(TBWBF[i+1,j] > SWMALES && SEX[j] == 0)

BEEFPRODACT[i,j] <- (MUSCLETISBF[i,j] + INTRAMFTISBF[i,j] + MISCFATTISBF[i,j]) else

if(TBWBF[i+1,j] > SWFEMALES && SEX[j] == 1 && REPRODUCTIVE[j] == 0)

BEEFPRODACT[i,j] <- (MUSCLETISBF[i,j] + INTRAMFTISBF[i,j] + MISCFATTISBF[i,j]) else

if(SEX[j] == 1 && FATFRACCARC[i,j] > MAXFATCARC & CALFWEANNR[i,j] ==

CALVESPERANIMAL[j] & TIME[i,j] > 800)

{BEEFPRODACT[i,j] <- (MUSCLETISBF[i,j] + INTRAMFTISBF[i,j] + MISCFATTISBF[i,j])} else

{BEEFPRODACT[i,j] = 0}

# Option 2: maximum number of years in (re)productive herd

if(TIME[i,j]/365 > MAXLIFETIME & BEEFPRODACT[i,j] == 0)

BEEFPRODACT[i,j] <- (MUSCLETISBF[i,j] + INTRAMFTISBF[i,j] + MISCFATTISBF[i,j])

if(REPRODUCTIVE[j] == 1 & CALFWEANNR[i,j] == CALVESPERANIMAL[j] & TIME[i,j]/365 >

MAXLIFETIME)

BEEFPRODACT[i,j] <- (MUSCLETISBF[i,j] + INTRAMFTISBF[i,j] + MISCFATTISBF[i,j])

# Option 3: cattle death

# If fat reserves are fully depleted, there is no beef production

if(MISCFATTISBF[i,j] < 0) BEEFPRODACT[i,j] <- -1

if(BEEFPRODACT[i,j]!=0) SLAUGHTERDAYACT[i,j] <- TIME[i,j] else

SLAUGHTERDAYACT[i,j] <- 9999

#########################################################################################

# Live weight production (kg total body weight per animal)

# Option 1: fat content reaches a specific level for cows, and CALFLIVENR should be met

# for cows

if(TBWBF[i+1,j] > SWMALES && SEX[j] == 0) LWPRODACT[i,j] <- TBWBF[i+1,j] else

if(TBWBF[i+1,j] > SWFEMALES && SEX[j] == 1 && REPRODUCTIVE[j] == 0)

LWPRODACT[i,j] <- TBWBF[i+1,j] else

if(SEX[j] == 1 && FATFRACCARC[i,j] > MAXFATCARC & CALFWEANNR[i,j] ==

CALVESPERANIMAL[j] & TIME[i,j] > 800) LWPRODACT[i,j] <- TBWBF[i+1,j] else

LWPRODACT[i,j] = 0

# Option 2: maximum number of years in (re)productive herd

if(TIME[i,j]/365 > MAXLIFETIME & BEEFPRODACT[i,j] == 0) LWPRODACT[i,j] <- TBWBF[i+1,j]

if(REPRODUCTIVE[j] == 1 & CALFWEANNR[i,j] == CALVESPERANIMAL[j] & TIME[i,j]/365 >

MAXLIFETIME) LWPRODACT[i,j] <- TBWBF[i+1,j]

# Option 3: cattle death

# If fat reserves are fully depleted, there is no live weight production

if(MISCFATTISBF[i,j] < 0) LWPRODACT[i,j] <- -1

#########################################################################################

# Carcass production (kg)

# Option 1: fat content reaches a specific level for cows, and CALFLIVENR should be met

# for cows

if(TBWBF[i+1,j] > SWMALES && SEX[j] == 0) CARCPRODACT[i,j] <- (MUSCLETISBF[i,j] +

INTRAMFTISBF[i,j] + MISCFATTISBF[i,j] + BONETISBF[i,j]) else

if(TBWBF[i+1,j] > SWFEMALES && SEX[j] == 1 && REPRODUCTIVE[j] == 0)

CARCPRODACT[i,j] <- (MUSCLETISBF[i,j] + INTRAMFTISBF[i,j] + MISCFATTISBF[i,j] +

BONETISBF[i,j]) else if(SEX[j] == 1 && FATFRACCARC[i,j] >

MAXFATCARC & CALFWEANNR[i,j] == CALVESPERANIMAL[j] &

TIME[i,j] > 800)

CARCPRODACT[i,j] <- (MUSCLETISBF[i,j] + INTRAMFTISBF[i,j] + MISCFATTISBF[i,j] +

BONETISBF[i,j]) else CARCPRODACT[i,j] = 0

# Option 2: maximum number of years in (re)productive herd

if(TIME[i,j]/365 > MAXLIFETIME & BEEFPRODACT[i,j] == 0)

CARCPRODACT[i,j] <- (MUSCLETISBF[i,j] + INTRAMFTISBF[i,j] + MISCFATTISBF[i,j] +

BONETISBF[i,j])

if(REPRODUCTIVE[j] == 1 & CALFWEANNR[i,j] == CALVESPERANIMAL[j] & TIME[i,j]/365 >

MAXLIFETIME) CARCPRODACT[i,j] <- (MUSCLETISBF[i,j] + INTRAMFTISBF[i,j] +

MISCFATTISBF[i,j] + BONETISBF[i,j])

# Option 3: cattle death

# If fat reserves are fully depleted, there is no carcass production

if(MISCFATTISBF[i,j] < 0) BEEFPRODACT[i,j] <- -1

#########################################################################################

# Day the animal is slaughtered (days)

# Is initially 9999, but is replaced by the correct number of days at slaughter

ENDDAY[j] <- min(SLAUGHTERDAYACT[1:i,j])

# Beef production at slaughter (kg per animal)

if(ENDDAY[j] < 9999) BEEFPROD[j] <- BEEFPRODACT[ENDDAY[j],j]

# Beef production (kg beef per head per year)

if(ENDDAY[j] < 9999) BEEFPRODYEAR[j] <- BEEFPRODACT[ENDDAY[j],j]/(TIME[ENDDAY[j],j]/365)

# Live weight production at slaughter (kg per animal)

if(ENDDAY[j] < 9999) LWPROD[j] <- LWPRODACT[ENDDAY[j],j]

# Live weight production (kg live weight per head per year)

if(ENDDAY[j] < 9999) LWPRODYEAR[j] <- LWPRODACT[ENDDAY[j],j]/(TIME[ENDDAY[j],j]/365)

# If the cow/bull is slaughtered, the weight is set to 0 via the vector ALIVE.

# ALIVE produces a vector that indicates whether the cow/bull is alive or slaughtered

# (1= true, 0=not true)

if(ENDDAY[j] == 9999) ALIVE[i+1,j] <- 1 else ALIVE[i+1,j] <- 0

# The code below keeps track of the parity of the reproductive cow

# Code indicates whether a cow is in or has had the nth parity (1= true, 0=not true).

if(CALFLIVENR[i,j] >= 1) PARITY1[i,j] = 1 else PARITY1[i,j] = 0

if(CALFLIVENR[i,j] >= 2) PARITY2[i,j] = 1 else PARITY2[i,j] = 0

if(CALFLIVENR[i,j] >= 3) PARITY3[i,j] = 1 else PARITY3[i,j] = 0

if(CALFLIVENR[i,j] >= 4) PARITY4[i,j] = 1 else PARITY4[i,j] = 0

if(CALFLIVENR[i,j] >= 5) PARITY5[i,j] = 1 else PARITY5[i,j] = 0

if(CALFLIVENR[i,j] >= 6) PARITY6[i,j] = 1 else PARITY6[i,j] = 0

if(CALFLIVENR[i,j] >= 7) PARITY7[i,j] = 1 else PARITY7[i,j] = 0

if(CALFLIVENR[i,j] >= 8) PARITY8[i,j] = 1 else PARITY8[i,j] = 0

if(CALFLIVENR[i,j] >= 9) PARITY9[i,j] = 1 else PARITY9[i,j] = 0

# Birth days of calves 1-9 (days after birth of the reproductive cow)

if(CALFLIVENR[i,j] == 1) BIRTHDAYCALF1 <- TIME[i]-sum(PARITY1[1:i,j]) else

BIRTHDAYCALF1 <- BIRTHDAYCALF1 # Birth day calf 1

if(CALFLIVENR[i,j] == 2) BIRTHDAYCALF2 <- TIME[i]-sum(PARITY2[1:i,j]) else

BIRTHDAYCALF2 <- BIRTHDAYCALF2 # Birth day calf 2

if(CALFLIVENR[i,j] == 3) BIRTHDAYCALF3 <- TIME[i]-sum(PARITY3[1:i,j]) else

BIRTHDAYCALF3 <- BIRTHDAYCALF3 # Birth day calf 3

if(CALFLIVENR[i,j] == 4) BIRTHDAYCALF4 <- TIME[i]-sum(PARITY4[1:i,j]) else

BIRTHDAYCALF4 <- BIRTHDAYCALF4 # Birth day calf 4

if(CALFLIVENR[i,j] == 5) BIRTHDAYCALF5 <- TIME[i]-sum(PARITY5[1:i,j]) else

BIRTHDAYCALF5 <- BIRTHDAYCALF5 # Birth day calf 5

if(CALFLIVENR[i,j] == 6) BIRTHDAYCALF6 <- TIME[i]-sum(PARITY6[1:i,j]) else

BIRTHDAYCALF6 <- BIRTHDAYCALF6 # Birth day calf 6

if(CALFLIVENR[i,j] == 7) BIRTHDAYCALF7 <- TIME[i]-sum(PARITY7[1:i,j]) else

BIRTHDAYCALF7 <- BIRTHDAYCALF7 # Birth day calf 7

if(CALFLIVENR[i,j] == 8) BIRTHDAYCALF8 <- TIME[i]-sum(PARITY8[1:i,j]) else

BIRTHDAYCALF8 <- BIRTHDAYCALF8 # Birth day calf 8

if(CALFLIVENR[i,j] == 9) BIRTHDAYCALF9 <- TIME[i]-sum(PARITY9[1:i,j]) else

BIRTHDAYCALF9 <- BIRTHDAYCALF9 # Birth day calf 9

#########################################################################################

# Average fraction of the diet digested (-)

AVGDIGFRAC[i,j] = FRACFEED1[i,j]\*FEED1[i,1] + FRACFEED2[i,j]\*FEED2[i,1] +

FRACFEED3[i,j]\*FEED3[i,1] + FRACFEED4[i,j]\*FEED4[1]

# Cumulative feed intake (kg DM per animal per day)

CUMULFEED1[i,j] = sum(FEED1QNTY[1:i,j]) # cumulative amount of feed type 1

CUMULFEED2[i,j] = sum(FEED2QNTY[1:i,j]) # cumulative amount of feed type 2

CUMULFEED3[i,j] = sum(FEED3QNTY[1:i,j]) # cumulative amount of feed type 3

CUMULFEED4[i,j] = sum(FEED4QNTY[1:i,j]) # cumulative amount of feed type 4

# Cumulative kg feed intake (whole diet) (kg DM per animal per day)

CUMULFEED[i,j] = sum(CUMULFEED1[i,j]+ CUMULFEED2[i,j] + CUMULFEED3[i,j] +

CUMULFEED4[i,j])

# Feed conversion ratio (FCR; kg feed per kg live weight)

FCR[i,j] = CUMULFEED[i,j]/(TBWBF[i,j]-TBWBF[1,j])

# Feed conversion ratio (kg feed per kg beef)

FCRBEEF[i,j] = CUMULFEED[i,j]/((MUSCLETISBF[i+1,j] + INTRAMFTISBF[i+1,j] +

MISCFATTISBF[i+1,j])-(MUSCLETISBF[1,j] + INTRAMFTISBF[1,j] +

MISCFATTISBF[1,j]))

# Feed conversion ratio (kg feed per kg beef at slaughter)

if(ENDDAY[j] < 9999) FCRBEEFENDDAY[j] <- CUMULFEED[ENDDAY[j]]/BEEFPROD[ENDDAY[j]]

# Percentage feed intake relative to the total body weight (%)

PERCFI[i,j] <- FEEDQNTY[i,j]/TBWBF[i,j]\*100

# Simulating one animal is sufficient for simulations at the animal level.

# The concept of the herd unit is used to simulate beef cattle at the herd level,

# where multiple animals are simulated (one reproductive cow and her offspring, minus a

# replacement heifer)

# If the animal is slaughtered, the time loop for the animal is terminated

if(SLAUGHTERDAYACT[i,j] < 9000) {breakFlagtime <- TRUE

break}

#########################################################################################

# } for the time loop

}

# Shift the weather files of the calves, based on their birthday

WEATHERCALF1 <- WEATHERORIG[BIRTHDAYCALF1:(imax[j]+BIRTHDAYCALF1+2),]

WEATHERCALF2 <- WEATHERORIG[BIRTHDAYCALF2:(imax[j]+BIRTHDAYCALF2+2),]

WEATHERCALF3 <- WEATHERORIG[BIRTHDAYCALF3:(imax[j]+BIRTHDAYCALF3+2),]

WEATHERCALF4 <- WEATHERORIG[BIRTHDAYCALF4:(imax[j]+BIRTHDAYCALF4+2),]

WEATHERCALF5 <- WEATHERORIG[BIRTHDAYCALF5:(imax[j]+BIRTHDAYCALF5+2),]

WEATHERCALF6 <- WEATHERORIG[BIRTHDAYCALF6:(imax[j]+BIRTHDAYCALF6+2),]

WEATHERCALF7 <- WEATHERORIG[BIRTHDAYCALF7:(imax[j]+BIRTHDAYCALF7+2),]

WEATHERCALF8 <- WEATHERORIG[BIRTHDAYCALF8:(imax[j]+BIRTHDAYCALF8+2),]

WEATHERCALF9 <- WEATHERORIG[BIRTHDAYCALF9:(imax[j]+BIRTHDAYCALF9+2),]

# Selects the right weather file for each calf

if(ORDER[j] == 0) {WEATHER <- WEATHERCALF1}

if(ORDER[j] == 1) {WEATHER <- WEATHERCALF2}

if(ORDER[j] == 2) {WEATHER <- WEATHERCALF3}

if(ORDER[j] == 3) {WEATHER <- WEATHERCALF4}

if(ORDER[j] == 4) {WEATHER <- WEATHERCALF5}

if(ORDER[j] == 5) {WEATHER <- WEATHERCALF6}

if(ORDER[j] == 6) {WEATHER <- WEATHERCALF7}

if(ORDER[j] == 7) {WEATHER <- WEATHERCALF8}

if(ORDER[j] == 8) {WEATHER <- WEATHERCALF9}

###########################################################################################

# Data on beef production and feed intake

# Beef production (kg per head)

BEEFPRODHERD[j] <- c(BEEFPRODACT[ENDDAY[j],j])

# Live weight production (kg per head)

LWPRODHERD[j] <- c(LWPRODACT[ENDDAY[j],j])

# Feed conversion ratio (kg DM feed per kg beef)

FCRHERDBEEF[j] <- c(FCRBEEF[ENDDAY[j],j])

# Cumulative feed intake whole life span (kg DM)

CUMULFEEDHERD[j] <- c(CUMULFEED[ENDDAY[j],j])

# Cumulative feed type 1 intake whole life span (kg DM)

CUMULFEED1HERD[j] <- c(CUMULFEED1[ENDDAY[j],j])

# Cumulative feed type 2 intake whole life span (kg DM)

CUMULFEED2HERD[j] <- c(CUMULFEED2[ENDDAY[j],j])

# Cumulative feed type 3 intake whole life span (kg DM)

CUMULFEED3HERD[j] <- c(CUMULFEED3[ENDDAY[j],j])

# Cumulative feed type 4 intake whole life span (kg DM)

CUMULFEED4HERD[j] <- c(CUMULFEED4[ENDDAY[j],j])

# Life span of the animal (years)

ANIMALYEARS[j] <- ENDDAY[j]/365

# Average weight (kg total body weight)

AVANWEIGHT[j] <- mean(TBWBF[1:ENDDAY[j],j])

# Average metabolic weight (kg empty body weight^0.75)

AVANMETWEIGHT[j] <- mean(EBWBFMET[1:ENDDAY[j],j])

# Vector with birthdays

# The reproductive cow in a herd unit is born at day 0

BIRTHDAY <- c(0,BIRTHDAYCALF1,BIRTHDAYCALF2,BIRTHDAYCALF3,BIRTHDAYCALF4,BIRTHDAYCALF5,

BIRTHDAYCALF6,BIRTHDAYCALF7,BIRTHDAYCALF8)

# Weaning time for calves (days after birth of the reproductive cow)

WNDAY <- BIRTHDAY+WEANINGTIME

WNDAY[1] <- ENDDAY[1]

# The vector ANIMALINFO lists key information on animal performance

ANIMALINFO <- cbind(REPRODUCTIVE[j], REPLACEMENT[j], PRODUCTIVE[j], SEX[j],

BEEFPRODHERD[j], CUMULFEEDHERD[j], FCRHERDBEEF[j], ANIMALYEARS[j],

AVANWEIGHT[j], AVANMETWEIGHT[j], ENDDAY[j], BIRTHDAY[j], WNDAY[j],

LWPRODHERD[j], CUMULFEED1HERD[j], CUMULFEED2HERD[j], CUMULFEED3HERD[j],

CUMULFEED4HERD[j])

# Information for individual animals is added to information for other animals in the

# herd unit

HERDINFO <- rbind(HERDINFO,ANIMALINFO)

# Runs are terminated before when the maximum number of calves per cow is reached.

# This saves processing time.

if(j == MAXCALFNR+1) {breakFlaganim <- TRUE

break}

} # } for the animal loop

###########################################################################################

# Upscaling to the herd level #

###############################################

HERDINFO1 <- rbind(HERDINFO, matrix(nrow=0, ncol=ncol(HERDINFO), data=0))

# Culling of reproductive cows, vector with probabilities for survival

# Culling starts after weaning the first calf

AZZAMCUMCORR <- c(CULL, (1-CULL)-(1-CULL)^2, (1-CULL)^2-(1-CULL)^3, (1-CULL)^3-(1-CULL)^4,

(1-CULL)^4-(1-CULL)^5, (1-CULL)^5-(1-CULL)^6, (1-CULL)^6-(1-CULL)^7,

(1-CULL)^7-(1-CULL)^8)

# Calculate chance that a cow is still in the herd after weaning a calf

AA <- (WNDAY[WNDAY >0]/365)-(GestPer+WEANINGTIME)/365 # Moment of conception (year)

BB <- floor(AA)+1 # Moment of conception rounded (year)

BB[1] <- 1

# Vector with probabilities for survival

# The probability for giving birth to the first calf (replacement) in a herd unit equals 1

CC <- AZZAMCUMCORR

CC[length(CC)] <- 1-sum(CC[1:length(CC)-1])

# Specification of key metrics for the reproductive cow over her total life span

# (accounting for culling)

REPRBEEF = NULL # Beef production (kg)

REPRLW = NULL # Live weight (kg)

REPRFEED = NULL # Feed intake (kg DM)

REPRFEED1 = NULL # Intake feed type 1 (kg DM)

REPRFEED2 = NULL # Intake feed type 2 (kg DM)

REPRFEED3 = NULL # Intake feed type 3 (kg DM)

REPRFEED4 = NULL # Intake feed type 4 (kg DM)

REPRFCR = NULL # Feed conversion ratio (kg DM feed per kg live weight)

REPRAVANW = NULL # Average total body weight (kg live weight)

REPRAVANWMET = NULL # Average metabolic body weight (kg0.75 empty body weight)

# Calculates the beef production and feed intake for different culling scenarios for the

# cow

for(p in 1:length(AA-8+MAXCALFNR)){

# Beef production (kg)

REPRBEEF[p] <- MUSCLETISBF[WNDAY[p],1] + INTRAMFTISBF[WNDAY[p],1] +

MISCFATTISBF[WNDAY[p],1]

# Live weight (kg)

REPRLW[p] <- TBWBF[WNDAY[p],1]

# Feed intake (kg DM)

REPRFEED[p] <- CUMULFEED[WNDAY[p],1]

# Intake feed type 1 (kg DM)

REPRFEED1[p] <- CUMULFEED1[WNDAY[p],1]

# Intake feed type 2 (kg DM)

REPRFEED2[p] <- CUMULFEED2[WNDAY[p],1]

# Intake feed type 3 (kg DM)

REPRFEED3[p] <- CUMULFEED3[WNDAY[p],1]

# Intake feed type 4 (kg DM)

REPRFEED4[p] <- CUMULFEED4[WNDAY[p],1]

# Feed conversion ratio (kg DM feed per kg live weight)

REPRFCR[p] <- FCR[WNDAY[p],1]

# Average total body weight (kg live weight)

REPRAVANW[p] <- mean(TBWBF[1:WNDAY[p],1])

# Average metabolic body weight (kg0.75 empty body weight)

REPRAVANWMET[p] <- mean(EBWBFMET[1:WNDAY[p],1])

}

CC1 <- CC # CC is duplicated

# Probabilities for the scenarios

CC1 <- c(0,CC1[1:8])

CC1 <- c(CC1,rep(0,(9-length(CC1))))

# Vector REPRINFO lists key information on the reproductive cow in a herd unit

REPRINFO <- matrix(nrow=(length(AA)), ncol = 18,

data= c(REPRODUCTIVE[1:length(AA)], REPLACEMENT[1:length(AA)],

PRODUCTIVE[1:length(AA)],SEX[1:length(AA)],REPRBEEF,REPRFEED,

REPRFCR, WNDAY[1:length(AA)]/365, REPRAVANW,REPRAVANWMET,

WNDAY[1:length(AA)], REPRLW, CC1, CC1, REPRFEED1, REPRFEED2,

REPRFEED3, REPRFEED4))

# Multiplies production and feed intake with probabilities (add up to a probability of 1)

REPRINFO1 <- REPRINFO \* CC1

# Lists production and feed intake of the cow, including the culling probabilities

REPRINFO2 <- colSums(REPRINFO1)

# works only at a MAXCALFNR equal to or higher than 3! (Otherwise warnings appear)

if(MAXCALFNR == 0) PRODINFO <- rep(0,18) else

if(MAXCALFNR < 3) PRODINFO <- HERDINFO1[3,] else PRODINFO <- HERDINFO1[3:(MAXCALFNR+1),]

# Probabilities for all animals in a herd unit to exist

DD <- c(1,1,(1-(CC[1])),(1-(sum(CC[1:2]))),(1-(sum(CC[1:3]))),(1-(sum(CC[1:4]))),

(1-(sum(CC[1:5]))),(1-(sum(CC[1:6]))), (1-(sum(CC[1:7]))),(1-(sum(CC[1:8]))),

(1-(sum(CC[1:9]))))

# Multiply production and feed intake of calves not used for replacement with probabilities

if(MAXCALFNR < 3) PRODINFO1 <- PRODINFO else PRODINFO1 <- PRODINFO \* DD[3:(MAXCALFNR+1)]

# Lists production and feed intake for calves not used for replacement, including the

# culling probabilities

if(MAXCALFNR < 3) PRODINFO2 <- PRODINFO else PRODINFO2 <- colSums(PRODINFO1)

# The vectors below list the information for the herd unit

HERDINFO2 <- colSums(rbind(REPRINFO2, PRODINFO2))

OUTPUTHERD <- rbind(REPRINFO2, PRODINFO2, HERDINFO2)

OUTPUT1 <- cbind(Metheatopt, TNRESP, ACTSW, LWRCOAT, CONVCOAT, SWR, TskinC, TcoatC, TAVGC,

MetheatBAL)

OUTPUT2 <- cbind(HERDINFO2[5], HERDINFO2[6], HERDINFO2[5]/HERDINFO2[6],

HERDINFO2[6]/HERDINFO2[5])

# Matrix with key information for one herd unit

OUTPUTHERDS <- rbind(OUTPUTHERDS,OUTPUTHERD)

# Feed efficiency (g beef kg DM intake) for the calves in a herd unit

FESENSIND[s] <- ANIMALINFO[5]/ANIMALINFO[6]\*1000

# Feed efficiency (g beef kg DM intake) for cow in a herd unit

FESENSREPR[s] <- OUTPUTHERDS[1,5]/OUTPUTHERDS[1,6]\*1000

# Feed efficiency (g beef kg DM intake) for the herd unit

FESENSHERD[s] <- OUTPUTHERDS[3,5]/OUTPUTHERDS[3,6]\*1000

###########################################################################################

} # End of the s-loop for sensitivity analysis

# Vector COLNAMES indicates the parameters used for sensitivity analysis (sensitivity

# analysis not performed in this code)

COLNAMES <- c("CoatConst", "ZC", "TbodyC", "LASMIN", "PHFEEDCAP", "RESPINCR",

"PROTFRACBONE", "PROTFRACMUSCLE", "LIPFRACMUSCLE", "PROTFRACFAT",

"LIPFRACFAT", "INCARC", "RUMENFRAC", "NEm", "NEpha", "BONEFRACMAX",

"LIPNONCMAX", "LIPNONCMIN", "PROTEFF", "LIPIDEFF", "DERMPL", "PROTNE",

"GestPer", "GESTINTERVAL", "WEANINGTIME","FtoConcW", "FATFACTOR", "RAINEXP",

"FRACVEG", "COMPFACT", "NEIEFFGEST", "CPGEST", "MILKDIG", "NEEFFMILK",

"PROTFRACMILK", "PROTEFFMILK", "COMPFACTTIS", "FATTISCOMP", "TTDIGINSC",

"DETOME", "DISSEFF",

"reflectivity coat", "coat length", "area corr",

"max body core-skin conductance", "birth weight", "milk A", "milk B",

"adult max. weight", "F", "milk A calf", "milk B calf",

"fraction TBW fertility", "maintenance factor", "min perc. for gestation",

"fat fraction bone parameter", "carcass fraction", "muscle:bone ratio",

"min. cond. core-skin. par.", "LHRskin A", "LHRskin B", "LHRskin C",

"BONE A", "BONE B", "MUSCLE A", "MUSCLE B", "INTRAMF A", "INTRAMF B",

"INTRAMF C", "PROTNONC A", "PROTNONC B", "RESP", "AREA A", "AREA B", "DIAM A",

"DIAM B", "BRR A", "BRR B", "BTV A", "TEXH A","TEXH B", "TEXH C","TEXH D",

"CBSMIN A", "CBSMIN B", "RAINFRAC", "RAINEVAP", "NEGEST", "GEMILK A",

"GEMILK B", "FATBONE A", "FATBONE B", "FATBONE C", "FATNONC A", "FATNONC B",

"FATNONC C", "FATNONC D","PROTNONC A", "PROTNONC B", "PROTNONC C",

"PROTNONC D", "PROTNONC E", "PHFEED A", "PHFEED B","NDFDIG A", "NDFDIG B",

"LUCAS A", "LUCAS B", "NONCGR A", "NONCGR B", "NRECYCL A", "NRECYCL B",

"NRECYCL C", "Reference")

# Feed efficiency for individual cattle under sensitivity analysis (not part of this code)

FESENSIND <- matrix(ncol=1, nrow=NPAR, data = FESENSIND)

#############################################################################################

# 3. Output section #

############################################################

############################################################

# Graph for cows #

############################################################

# 1. TBW over time

if(SCALE==1) maxgr <- 1000 else maxgr <- 4000

layout(matrix(c(1,1,2,2,3,3), 3, 2, byrow = TRUE),

widths=c(1,1,1), heights=c(1.8,1.1,1.4))

par(mar=c(0.5,8,1,2))

plot(TBW[1:maxgr,1]~c(1:maxgr), type = "l", ylim = c(0,LIBRARY[13]), las=1,

xlab = "age (days)", ylab = "TBW (kg)", xaxt = "n", lty = "solid", lwd = 1.5, xaxs = "i",

yaxs = "i")

lines(TBWBF[1:maxgr,1]~c(1:maxgr), lty = "dashed", lwd = 1.5)

legend("topleft", c("Genetic potential TBW", "Simulated TBW"),

col= c("black","black"),

lty = c("solid", "dashed"),

bty = "n")

# 2. Feed intake over time

bars <- rbind(FEED1QNTY[1:maxgr],FEED2QNTY[1:maxgr],FEED3QNTY[1:maxgr],FEED4QNTY[1:maxgr])

if(FEEDNR[z]==2) bars <- rbind(FEED1QNTY[1:maxgr],FEED2QNTY[1:maxgr]-FEED2QNTY[1:maxgr]\*

HOUSING1[1:maxgr], FEED2QNTY[1:maxgr]\*HOUSING1[1:maxgr])

if(FEEDNR[z]==4) bars <- rbind(FEED1QNTY[1:maxgr],FEED3QNTY[1:maxgr]-FEED3QNTY[1:maxgr]\*

HOUSING1[1:maxgr], FEED3QNTY[1:maxgr]\*HOUSING1[1:maxgr])

if(FEEDNR[z]==5) bars <- rbind(FEED1QNTY[1:maxgr],FEED2QNTY[1:maxgr]-FEED2QNTY[1:maxgr]\*

HOUSING1[1:maxgr], FEED2QNTY[1:maxgr]\*HOUSING1[1:maxgr])

bars[,ENDDAY[1]:maxgr] <- NA

par(mar=c(0.5,8,0.5,2))

plot(0~0, xaxt="n", yaxt="n", pch = 19, col="white", ylab="", xlab="", xaxs = "i")

par(new=T)

if(FEEDNR[z]==1){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19), xaxs= "i",

col= c("gold","darkkhaki"), las=1,

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Hay","Wheat"),

fill = c("darkkhaki","gold"),

cex=1, bty = "n")}

if(FEEDNR[z]==2){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19),xaxs= "i",

col= c("orange","darkkhaki","seagreen"),las=1,

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Grass","Hay","Barley"),

fill = c("seagreen","darkkhaki","orange"),

cex=1, bty = "n")}

if(FEEDNR[z]==3){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19),xaxs= "i",

col= c("orange","seagreen"),las=1,

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Grass","Barley"),

fill = c("seagreen","orange"),

cex=1, bty = "n")}

if(FEEDNR[z]==4){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19),xaxs= "i",

col= c("orange","darkkhaki","seagreen"), las=1,

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Grass","Hay","Barley"),

fill = c("seagreen","darkkhaki","orange"),

cex=1, bty = "n")}

if(FEEDNR[z]==5){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19),xaxs= "i",

col= c("orange","darkkhaki","seagreen"), las=1,

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Grass","Hay","Barley"),

fill = c("seagreen","darkkhaki","orange"),

cex=1, bty = "n")}

# 3. Defining and limiting factors for growth over time

HEATSTRESS <- REDHP

HEATSTRESS[HEATSTRESS<0] <- 4.5

HEATSTRESS[HEATSTRESS!=4.5] <- NA

COLDSTRESS1 <- Metheatcold-HEATIFEEDMAINTWM

COLDSTRESS <- COLDSTRESS1

COLDSTRESS[COLDSTRESS>0] <- 3.5

COLDSTRESS[COLDSTRESS!=3.5] <- NA

FILLGITGRAPH <- FILLGIT

FILLGITGRAPH[FILLGITGRAPH>=0.97] <-2.5

FILLGITGRAPH[FILLGITGRAPH!=2.5] <-NA

PROTGRAPH <- PROTBAL

PROTGRAPH[PROTGRAPH<0] <- 0.5

PROTGRAPH[PROTGRAPH!=0.5] <- NA

PROTGRAPH[FILLGITGRAPH>=0.999] <- NA

HEATSTRESS[is.na(HEATSTRESS)] <- 0

COLDSTRESS[is.na(COLDSTRESS)] <- 0

FILLGITGRAPH[is.na(FILLGITGRAPH)] <- 0

PROTGRAPH[is.na(PROTGRAPH)] <- 0

TBWBF[is.na(TBWBF)] <- 0

if(FEEDNR[z] == 5) FEEDQNTYTOT <- FEEDQNTYTOT[1:(imax[1]+1)] \* TBWBF/100

NELIM <- FEEDQNTYTOT[1:imax[1]] - FEEDQNTY

NELIM <- NELIM + HEATSTRESS + PROTGRAPH + FILLGITGRAPH

NELIM[NELIM>0.00001] <- NA

NELIM[NELIM<-0.00001] <- NA

NELIM[ENDDAY[1]:maxgr] <- NA

NELIM[NELIM<0.00001] <- 1.5

NELIM[NELIM>-0.00001] <- 1.5

NELIM[is.na(NELIM)] <- 0.0

GENLIM <- HEATSTRESS + FILLGITGRAPH + PROTGRAPH + NELIM

GENLIM[GENLIM > 0] <- NA

GENLIM[GENLIM == 0] <- 5.5

GENLIM[ENDDAY[1]:maxgr] <- NA

HEATSTRESS[HEATSTRESS==0] <- NA

COLDSTRESS[COLDSTRESS==0] <- NA

FILLGITGRAPH[FILLGITGRAPH==0] <- NA

NELIM[NELIM==0] <- NA

PROTGRAPH[PROTGRAPH==0] <- NA

par(mar=c(5,8,0.5,2))

plot(HEATSTRESS[1:maxgr,1]~c(1:maxgr), pch = "|", col="#D55E00", cex = 0.9,

ylim = c(0.3,5.8), xlab = "Age (days)", ylab = NA, yaxt = "n", xaxs = "i")

axis(2,at = c(0.5:5.5), labels = c("protein", "energy","digestion cap.", "cold stress",

"heat stress", "genotype"), las = 1, cex.axis = 1.0)

points(COLDSTRESS[1:maxgr,1]~c(1:maxgr), pch = "|", col="#0072B2", cex = 0.9)

points(FILLGITGRAPH[1:maxgr,1]~c(1:maxgr), pch = "|", col="#009E73", cex = 0.9)

points(NELIM[1:maxgr,1]~c(1:maxgr), pch = "|", col="#E69F00", cex = 0.9)

points(PROTGRAPH[1:maxgr,1]~c(1:maxgr), pch = "|", col="#CC79A7", cex = 0.9)

points(GENLIM[1:maxgr,1]~c(1:maxgr), pch = "|", col="#999999", cex = 0.9)

# Lists of the defining and limiting factors

GENLIMdata <- cbind(GENLIMdata, GENLIM[1:4000])

HEATSTRESSdata <- cbind(HEATSTRESSdata, HEATSTRESS[1:4000])

COLDSTRESSdata <- cbind(COLDSTRESSdata, COLDSTRESS[1:4000])

FILLGITGRAPHdata <- cbind(FILLGITGRAPHdata, FILLGITGRAPH[1:4000])

NELIMdata <- cbind(NELIMdata, NELIM[1:4000])

PROTGRAPHdata <- cbind(PROTGRAPHdata, PROTGRAPH[1:4000])

#############################################################################################

# Graph for calves #

############################################################

# 1. TBW over time

maxgr <- 1000

layout(matrix(c(1,1,2,2,3,3), 3, 2, byrow = TRUE),

widths=c(1,1,1), heights=c(1.8,1.1,1.4))

# Plot on body weight dynamics

par(mar=c(0.5,8,1,2))

plot(TBW[1:maxgr,3]~c(1:maxgr), type = "l", ylim = c(0,LIBRARY[13]),

xlab = "age (days)", ylab = "TBW (kg)", xaxt = "n", lty = "solid", lwd = 1.5,

xaxs = "i", yaxs = "i")

lines(TBWBF[1:ENDDAY[3],3]~c(1:ENDDAY[3]), lty = "dashed", lwd = 1.5)

legend("topleft", c("Genetic potential TBW", "Simulated TBW"),

col= c("black","black"),

lty = c("solid", "dashed"),

bty = "n")

# 2. feed intake over time

bars <- rbind(FEED1QNTY[1:maxgr,3],FEED2QNTY[1:maxgr,3],FEED3QNTY[1:maxgr,3],

FEED4QNTY[1:maxgr,3])

if(FEEDNR[z]==2) bars <-rbind(FEED1QNTY[1:maxgr,3],FEED2QNTY[1:maxgr,3]-FEED2QNTY[1:maxgr,3]\*

HOUSING[1:maxgr], FEED2QNTY[1:maxgr,3]\*HOUSING[1:maxgr])

if(FEEDNR[z]==4) bars <-rbind(FEED1QNTY[1:maxgr,3],FEED3QNTY[1:maxgr,3]-FEED3QNTY[1:maxgr,3]\*

HOUSING[1:maxgr], FEED3QNTY[1:maxgr,3]\*HOUSING[1:maxgr])

if(FEEDNR[z]==5) bars <-rbind(FEED1QNTY[1:maxgr,3],FEED2QNTY[1:maxgr,3]-FEED2QNTY[1:maxgr,3]\*

HOUSING[1:maxgr], FEED2QNTY[1:maxgr,3]\*HOUSING[1:maxgr])

bars[,ENDDAY[3]:maxgr] <- NA

par(mar=c(0.5,8,0.5,2))

plot(0~0, xaxt="n", yaxt="n", pch = 19, col="white", ylab="", xlab="", xaxs = "i")

par(new=T)

if(FEEDNR[z]==1){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19),xaxs="i",

col= c("gold","darkkhaki"),

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Hay","Wheat"),

fill = c("darkkhaki","gold"),

cex=1, bty = "n")}

if(FEEDNR[z]==2){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19),xaxs= "i",

col= c("orange","darkkhaki","seagreen"),

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Grass","Hay","Barley"),

fill = c("seagreen","darkkhaki","orange"),

cex=1, bty = "n")}

if(FEEDNR[z]==3){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19),xaxs= "i",

col= c("orange","seagreen"),

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Grass","Barley"),

fill = c("seagreen","orange"),

cex=1, bty = "n")}

if(FEEDNR[z]==4){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19),xaxs= "i",

col= c("orange","darkkhaki","seagreen"),

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Grass","Hay","Barley"),

fill = c("seagreen","darkkhaki","orange"),

cex=1, bty = "n")}

if(FEEDNR[z]==5){

barplot(as.matrix(bars), space = 0, border = NA, xaxt = "n", ylim=c(0,19),xaxs= "i",

col= c("orange","darkkhaki","seagreen"),

ylab = expression(paste("Feed intake (kg day"^"-1"\*")")))

legend("topleft",

legend=c("Grass","Hay","Barley"),

fill = c("seagreen","darkkhaki","orange"),

cex=1, bty = "n")}

# 3. Defining and limiting factors for growth over time

HEATSTRESS <- REDHP

HEATSTRESS[HEATSTRESS<0] <- 4.5

HEATSTRESS[HEATSTRESS!=4.5] <- NA

COLDSTRESS1 <- Metheatcold-HEATIFEEDMAINTWM

COLDSTRESS <- COLDSTRESS1

COLDSTRESS[COLDSTRESS>0] <- 3.5

COLDSTRESS[COLDSTRESS!=3.5] <- NA

FILLGITGRAPH <- FILLGIT

FILLGITGRAPH[FILLGITGRAPH>=0.97] <-2.5

FILLGITGRAPH[FILLGITGRAPH!=2.5] <-NA

PROTGRAPH <- PROTBAL

PROTGRAPH[PROTGRAPH<0] <- 0.5

PROTGRAPH[PROTGRAPH!=0.5] <- NA

PROTGRAPH[FILLGITGRAPH>=0.999] <- NA

HEATSTRESS[is.na(HEATSTRESS)] <- 0

COLDSTRESS[is.na(COLDSTRESS)] <- 0

FILLGITGRAPH[is.na(FILLGITGRAPH)] <- 0

PROTGRAPH[is.na(PROTGRAPH)] <- 0

TBWBF[is.na(TBWBF)] <- 0

if(FEEDNR[z] == 5) FEEDQNTYTOT <- FEEDQNTYTOT \* TBWBF/100

NELIM <- c(rep(FEEDQNTYTOT[1:4000],9)) - FEEDQNTY

NELIM <- NELIM + HEATSTRESS + PROTGRAPH + FILLGITGRAPH

NELIM[NELIM>0.00001] <- NA

NELIM[NELIM<-0.00001] <- NA

NELIM[NELIM<0.00001] <- 1.5

NELIM[NELIM>-0.00001] <- 1.5

NELIM[ENDDAY[3]:maxgr] <- NA

NELIM[is.na(NELIM)] <- 0.0

GENLIM <- HEATSTRESS + FILLGITGRAPH + PROTGRAPH + NELIM

GENLIM[GENLIM > 0] <- NA

GENLIM[GENLIM == 0] <- 5.5

GENLIM[ENDDAY[3]:maxgr] <- NA

HEATSTRESS[HEATSTRESS==0] <- NA

COLDSTRESS[COLDSTRESS==0] <- NA

FILLGITGRAPH[FILLGITGRAPH==0] <- NA

NELIM[NELIM==0] <- NA

PROTGRAPH[PROTGRAPH==0] <- NA

par(mar=c(5,8,0.5,2))

plot(HEATSTRESS[1:maxgr,3]~c(1:maxgr), pch = "|", col="#D55E00", cex = 0.9,

ylim = c(0.3,5.8), xlab = "Age (days)", ylab = NA, yaxt = "n", xaxs = "i")

axis(2,at = c(0.5:5.5), labels = c("protein", "energy","digestion cap.", "cold stress",

"heat stress", "genotype"), las = 1, cex.axis = 1.0)

points(COLDSTRESS[1:maxgr,3]~c(1:maxgr), pch = "|", col="#0072B2", cex = 0.9)

points(FILLGITGRAPH[1:maxgr,3]~c(1:maxgr), pch = "|", col="#009E73", cex = 0.9)

points(NELIM[1:ENDDAY[3],3]~c(1:ENDDAY[3]), pch = "|", col="#E69F00", cex = 0.9)

points(PROTGRAPH[1:maxgr,3]~c(1:maxgr), pch = "|", col="#CC79A7", cex = 0.9)

points(GENLIM[1:ENDDAY[3],3]~c(1:ENDDAY[3]), pch = "|", col="#999999", cex = 0.9)

# End of the graph for calves

#############################################################################################

# Table with key information about cattle performance (information also presented in Table 3,

# paper Van der Linden et al. (2017a))

DATAt3 <-c(FESENSHERD[s], FESENSREPR[s], FESENSIND[s], OUTPUTHERDS[1,6]/OUTPUTHERDS[3,6],

OUTPUTHERDS[3,5], OUTPUTHERDS[1,5], OUTPUTHERDS[2,5], TBWBF[ENDDAY[3],3])

TABLEDATA <- matrix(ncol=1, nrow=8, data=DATAt3)

colnames(TABLEDATA) <- "Herd level"

rownames(TABLEDATA) <- c("Feed efficiency herd unit (g beef kg-1 DM)",

"Feed efficiency repr. cow (g beef kg-1 DM)",

"Feed efficiency bull calf (g beef kg-1 DM)",

"Feed fraction repr. cow (-)", "Beef production herd unit (kg)",

"Beef production repr. cow (kg)", "Beef production bull calf (kg)",

"Slaughter weight bull calf (kg)")

print("Case number") # Case number corresponds to the case number in Table 3

print(z) # z is the case number

print(TABLEDATA)

} # End z-loop for the cases