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## Development and evaluation of the herd dynamic milk (HDM) model with focus on the individual cow component --Manuscript Draft--

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<b>Abstract:</b>	<p>The Herd Dynamic Milk model (HDM) is a dynamic model capable of simulating the performance of individual dairy animals (from birth to death), with a daily time step. Within this study the HDM model is described and evaluated in relation to milk production, body condition score (BCS) and BCS change throughout lactation by comparing model simulations against data from published experimental studies. The model's response to variation in genetic potential, herbage allowance and concentrate supplementation was tested in a sensitivity analysis. Data from experiments in Ireland and France over a 3 year period (2009 to 2011) were used to complete the evaluation. The aim of the Irish experiment was to determine the impact of different stocking rates (SR) (SR1: 3.28 SR2: 2.51 cow/ha) on key physical, biological and economic performance. The aim of the French experiment was to evaluate over a prolonged time period, the ability of two breeds of dairy cows (Holstein and Normande) to produce and to reproduce under two feeding strategies (high level and low level) in the context of compact calving. The model evaluation was conducted at the herd level with separate evaluations for the primiparous and multiparous cows. The evaluation included the two extreme stocking rates for the Irish experiment, and an evaluation at the overall herd and individual animal level for the different breeds and feeding levels for the French data. The comparison of simulation and experimental data for all scenarios resulted in a relative prediction error, which was consistently lower than 15% across experiments for weekly milk production and BCS. In relation to BCS, the highest root mean square error was 0.27 points of BCS which arose for Holstein cows in the low feeding group in late lactation. The model responded in a realistic fashion to variation in genetic potential for milk production, herbage allowance and concentrate supplementation.</p>

1 **Development and evaluation of the herd dynamic milk (HDM) model with focus**  
2 **on the individual cow component**

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14

15 Short title: Evaluation of the herd dynamic milk (HDM) model.

16 **Abstract**

17 The Herd Dynamic Milk model (HDM) is a dynamic model capable of simulating the  
18 performance of individual dairy animals (from birth to death), with a daily time step.  
19 Within this study the HDM model is described and evaluated in relation to milk  
20 production, body condition score (BCS) and BCS change throughout lactation by  
21 comparing model simulations against data from published experimental studies. The  
22 model's response to variation in genetic potential, herbage allowance and  
23 concentrate supplementation was tested in a sensitivity analysis. Data from  
24 experiments in Ireland and France over a 3 year period (2009 to 2011) were used to  
25 complete the evaluation. The aim of the Irish experiment was to determine the  
26 impact of different stocking rates (**SR**) (SR1: 3.28 SR2: 2.51 cow/ha) on key  
27 physical, biological and economic performance. The aim of the French experiment  
28 was to evaluate over a prolonged time period, the ability of two breeds of dairy cows  
29 (Holstein and Normande) to produce and to reproduce under two feeding strategies  
30 (high level and low level) in the context of compact calving. The model evaluation  
31 was conducted at the herd level with separate evaluations for the primiparous and  
32 multiparous cows. The evaluation included the two extreme stocking rates for the  
33 Irish experiment, and an evaluation at the overall herd and individual animal level for  
34 the different breeds and feeding levels for the French data. The comparison of  
35 simulation and experimental data for all scenarios resulted in a relative prediction  
36 error, which was consistently lower than 15% across experiments for weekly milk  
37 production and BCS. In relation to BCS, the highest root mean square error was 0.27  
38 points of BCS which arose for Holstein cows in the low feeding group in late  
39 lactation. The model responded in a realistic fashion to variation in genetic potential  
40 for milk production, herbage allowance and concentrate supplementation.

41 **Keywords:** modelling; model evaluation; dairy cows; milk yield; body condition score

42

### 43 **Implication**

44 A new model has been developed which can simulate milk production and body  
45 condition score change of dairy cows through lactation under grazing conditions. For  
46 both milk production and body condition score change the model shows good  
47 accuracy. From a farmer's perspective, the model, once adapted with an user-  
48 friendly interface, can be used at individual animal level or at a herd level. Clear  
49 management practices can be tested by applying certain strategies around pasture  
50 and animal management to determine their effects on milk production and body  
51 condition score change.

52

### 53 **Introduction**

54 Modelling dairy systems can be complex due to the interactions between all the  
55 intrinsic components of the cow (breed, genetic potential, parity, etc) but also due to  
56 the interaction of the animal with the environment (feeding system, type of housing,  
57 time of year, stage of lactation, etc) and the management (dairy farmer decisions) to  
58 which animals are subjected (nutrition status, breeding, etc) (Buckley *et al.*, 2003,  
59 Martin and Sauvant, 2010a). A model if useful must be capable of simulating all of  
60 the components of a system in a realistic fashion and the model must be capable of  
61 reacting to the changing components of the system. The ever increasing pressures  
62 placed on farmers due to changing circumstances (e.g. milk price volatility and  
63 climate change) means that there is increased pressure with all decisions taken on  
64 the farm. Having a model that can react in a meaningful way across these different  
65 questions allows farmers to optimise their decision making process continually. For

66 example, when feeding the dairy cow, predicting the partition between milk  
67 production and body condition score change throughout lactation either in grazing or  
68 indoor feeding would allow better decisions to be made on farm but these challenges  
69 present a major obstacle for modelers all over the world (Friggens *et al.*, 2004,  
70 Faverdin *et al.*, 2011, Baudracco *et al.*, 2012). The model presented here deals with  
71 this issue in a grazing context.

72 A key feature in the development of a model is the evaluation and validation step.  
73 The most common way to validate a model is to compare with existing experimental  
74 data. The E-Cow model Baudracco *et al.* (2012) has been evaluated using two  
75 independent experimental datasets from New-Zealand and Argentina. The statistical  
76 analyses used were the concordance correlation coefficient (**CCC**) and the relative  
77 prediction error (**RPE**) to evaluate the daily herbage dry matter intake, the milk yield  
78 and live weight change. The milk production and herbage intake of the French model  
79 GrazIN (Delagarde *et al.*, 2011a, Faverdin *et al.*, 2011) was validated by comparing  
80 model outputs against experimental data using the mean square prediction error on  
81 206 experimental herds (Delagarde *et al.*, 2011b).

82 The objective of this paper was to present and evaluate a new model in terms of milk  
83 production and BCS prediction. The strength of this model lies on an update of the  
84 idea of the partition of the energy and protein intake between the milk production and  
85 the body reserve in pasture based systems (Bruce *et al.*, 1984). The goal was to  
86 integrate the genetic progress and its consequences in terms of intake, BCS change  
87 in the partition of the nutrient intake depending on the lactation stage and the  
88 genetics of the animal. Data from two different studies in two different countries  
89 (Ireland and France) which operate grass based systems of differing levels of  
90 intensity and supplementation were used to evaluate the model. The model has also

91 been evaluated on its ability to respond to changes in genetics of the animals,  
92 herbage allowance and concentrate supplementation with outputs compared to  
93 expected outputs based on published literature.

94

## 95 **Materials and methods**

96 The Herd Dynamic Milk model (**HDM**) is a dynamic model developed in C++ capable  
97 of simulating the performance of dairy animals (from birth to death) individually, with  
98 a daily time step. Briefly, the model allows differentiated management of different  
99 groups of animals (mainly through feeding). The groups included are calves (0 – 90  
100 days), three groups of heifers (90 days to 365 days, 12 to 24 months and over 24  
101 months), lactating cows and the dry cows. Each animal is simulated individually  
102 permitting a precise representation of each animal on the farm. At calving, the dam  
103 (heifer or cow) is transferred from the heifer or dry cow group to the lactating cow  
104 group and one or two calves are added to the calf groups depending on the  
105 prolificacy (adjusting for mortality). This paper will describe in detail the cow  
106 component of the model during lactation in terms of milk production and BCS  
107 change. The young stock, dry cow, fertility and mortality aspect are described in the  
108 supplementary material. A flow diagram of the lactation element of the model is  
109 presented in Figure 1.

110 *Figure 1 around here*

111

### 112 *Inputs and Outputs of the model*

113 The initial herd demography is specified via the description of the individual animals  
114 presented at the start of the simulation. The information required for every animal is  
115 age (day); body weight (**BW**) (kg); theoretical potential maximum milk yield (kg/d) for

116 the calf (used when she becomes a cow), heifer and cow; as well as the day in  
117 gestation and the number of inseminations (since the last calving for the cows) for  
118 the heifer and cow; and finally the day in lactation and the BCS and BCS at calving  
119 for the cow. The BCS scale used within this model is the 0 to 5 scale (Bazin *et al.*,  
120 1984). The theoretical potential maximum milk yield is defined as the theoretical  
121 maximum daily milk production of the mature cow (parity 3 and more) at peak of  
122 lactation with a static BCS and BW. The period of simulation is expressed in monthly  
123 time blocks and can be from one month to at least in theory an infinite time. The  
124 initialisation of the model also requires the user to input key management decisions  
125 which include the maximum number of animals on farm, information about  
126 insemination (breeding period; maximum number of inseminations), dry off (specific  
127 date or day in lactation) and culling criteria. In terms of feeding, the herbage  
128 allowance, feed energy and protein content are needed as well as allocation of  
129 supplementary feed whether concentrate or forage. The main daily outputs of this  
130 model are the dry matter intake, milk production, BCS and BW for every animal for  
131 everyday of the year. These outputs can be summarised for the cattle by week of  
132 lactation or by week of the year. The total milk produced per cow per lactation is also  
133 available.

134

### 135 *Herd feeding and dairy cow performance*

136 The model incorporates the French feeding system (Faverdin *et al.*, 2010, Faverdin  
137 *et al.*, 2011) which was modified to integrate milk production, BCS and BCS change  
138 of animals. In this paper, the milk output from the model is expressed in kg of  
139 standard milk (**MY**) at 4.0 % of fat and 3.1 % of protein content, corresponding to the  
140 equation of Faverdin *et al.* (2010) (Supplementary Equation S12).



141

142 *Intake and nutrient supply.* The INRA feeding system (INRA, 2010) was selected to  
143 model the nutrient intake within the model. The intake when housed and at grazing is  
144 calculated based on the GrazeIn model as described in (Delagarde *et al.*, 2011a,  
145 Delagarde *et al.*, 2011b, Faverdin *et al.*, 2011). In simple terms, intake of the animal  
146 is the lesser of the intake permitted by the intake capacity and fill value of the feed,  
147 the herbage allowance and the intake needed to meet the requirements. The intake  
148 at grazing is calculated depending on the possible intake of the housed animal  
149 corrected for herbage allowance and time at pasture. The quality of the forage or  
150 grass is characterised by its energy value (**UFL** "unité fouragère lait"), protein (**PDI**  
151 "protéine digestible dans l'intestin) and **FV** (Fill Value). The FV of a forage is an  
152 inverse function of its ingestibility and is calculated by the ratio of intake of the  
153 reference forage to voluntary dry matter intake of the considered forage (Faverdin *et*  
154 *al.*, 2011). The quality of the concentrate is determined by its UFL and PDI. The  
155 concentrate has no fixed FV, its FV is calculated dependent on the substitution rate  
156 between concentrate and forage which represents the metabolic regulation of intake  
157 and depends on the percentage of concentrate and the total energetic value of the  
158 diet (Faverdin *et al.*, 2011).

159

160 *Calculation of the theoretical milk yield (theoMY) and maximum theoretical*  
161 *Mobilisation (theoMOBmax).* In this model, the BCS change and the milk yield are  
162 modelled together in an interlinked way depending on the interaction between the  
163 nutrient, feed intake and partition. These two components depend mainly on two  
164 factors:

165 Factor 1 - A BCS pool at calving (**theoMOBmax**), expressed in units of BCS.  
166 This BCS pool gives the theoretical maximum mobilisation of the dairy cow through  
167 the lactation,

168 Factor 2 - The gap (**MYgap**) between the theoretical milk yield of the cow and  
169 the milk yield allowed by her energy intake, expressed in kg of milk.

170

171 The theoretical milk yield of the cow is driven by her maximum theoretical milk yield  
172 (**theoMYmax**), expressed in kg of standard milk and is dependent on the parity and  
173 the day of lactation (**LacD**):

174  $theoMY = coeff\_parity \times theoMYmax \times (0.27 + 6.47 \times e^{-0.013 \times LacD} - 6.20 \times e^{-0.017 \times LacD})$  (1) for  
175 primiparous,

176  $theoMY = coeff\_parity \times theoMYmax \times (0.25 + 2.95 \times e^{-0.015 \times LacD} - 2.70 \times e^{-0.028 \times LacD})$  (2) for  
177 multiparous.

178 With  $coeff\_parity=0.75$  for parity 1, 0.92 for parity 2 and 1 otherwise (Hutchinson *et*  
179 *al.*, 2013).

180 The shape of the lactation profiles originates from a previous study of Masselin *et al.*  
181 (1987) which described many classical lactation curve models based on the  
182 theoMYmax. The theoMYmax expresses the cow's milk production potential in terms  
183 of her estimated yields at peak lactation in the third parity. The equations have then  
184 been adjusted using previously published data from INRA (Delaby *et al.*, 2009) and  
185 Teagasc (Horan *et al.*, 2004). Those data originates from experiments where cows  
186 spend most of their lactation at grazing.

187 The theoMOBmax (equation 3), which is the maximum possible BCS change  
188 through the lactation, is set at calving and is always negative. The equation was  
189 developed by Delaby *et al.* (2010a) for different breeds. It has been calculated using

190 data with a large range of BCS loss and *theoMYmax* for primiparous and multiparous  
191 cows (Delaby *et al.*, 2010a):

$$192 \quad \textit{theoMOBmax} = 2.2 + \textit{parity} - 0.047 \times \textit{theoMYmax} \times \textit{coeff\_parity} - 0.51 \times \textit{BCS}_{\textit{calv}} \quad (3)$$

193 with *parity* = -0.1 for primiparous and + 0.1 for multiparous, *BCS\_calv* the BCS of the  
194 cow at calving and the *theoMOBmax* expressed in units of BCS and  
195 *coeff\_parity*=0.75 for party 1, 0.92 for parity 2 and 1 otherwise (Hutchinson *et al.*,  
196 2013).

197

198 *Calculation of the milk yield allowed by the energy intake (uflMY)*. It has been shown  
199 in French studies at grazing (Hoden *et al.*, 1991) that the milk production of any one  
200 day is more influenced by the previous day's nutrition than it is by the direct feed  
201 intake on that day. This component of individual animal performance is included in  
202 the model with the milk production allowed by the diet depending on the feedstuff  
203 ingested in the two previous days (Jacquot, 2012):

$$204 \quad \textit{uflMY} = \frac{0.3 \times \textit{UFLint}_{D-2} + 0.7 \times \textit{UFLint}_{D-1} - \textit{UFLreq} - E}{0.44} \quad (4).$$

205 With *UFLint<sub>D-1</sub>* the UFL ingested the previous day, *UFLint<sub>D-2</sub>* the UFL ingested two  
206 days before and 0.44 corresponding to a requirement of 0.44 UFL per kg of milk at 4  
207 % of fat content (Supplementary Equation S12).

208 The UFL requirement (**UFLreq**) consists of the energy for maintenance, gestation  
209 and growth (Faverdin *et al.*, 2010) (Supplementary Equation S1 to S6). *E* is a  
210 correction factor for net energy taking into account the negative effect of feeding  
211 level and concentrate feeding level has on the organic matter digestibility and energy  
212 valorisation of the ration (Faverdin *et al.*, 2011) (Supplementary Equation S5).

213 The milk yield gap (**MYgap**) of the animal is the difference between the milk yield  
214 allowed by the UFL intake and the theoretical milk yield and is expressed in kg of  
215 milk:

$$216 \quad MYgap = uflMY - theoMY \quad (5).$$

217  
218 *Calculation of the daily milk yield (MY).* The animal response is calculated depending  
219 on the MYgap sign. When MYgap is positive then the cow has surplus energy to  
220 partition between additional milk and body condition score deposition, when MYgap  
221 is negative the cow is in deficit of energy and adjusts milk and body condition score  
222 accordingly. It is firstly assumed that the diet is well balanced in terms of PDI  
223 (PDIint/UFLint=100) (Vérité and Delaby, 2000), with PDIint and UFLint the PDI and  
224 UFL ingested during the day.

225 The shape of the equation 6 and 7 has been generated to take into account the fact  
226 that the responses are linked to the potential of the animal and to the available  
227 energy. Those equations have been validated based on external data from INRA in  
228 LePin (Delaby *et al.*, 2003, Delaby *et al.*, 2009)

229 If the energy intake is higher than the requirement for theoretical milk yield  
230 (MYgap>0), the cow is able to produce more milk than the theoretical milk yield. The  
231 extra energy is used partly to produce more milk and partly to gain body reserve  
232 (through BCS and BW gain). The milk yield response rule included is curvilinear,  
233 thus it increases with theoMY and with the MYgap based on the exponential  
234 equation:

$$235 \quad bcsMYresp = MYgap \times \left[ (0.57 + 0.012 \times theoMY) \times e^{-0.023 \times MYgap} \right] \quad (6)$$

236 with bcsMYresp the response in kg of milk, this response is added to the theoretical  
237 milk yield.

238

239 If the energy intake is lower than the requirement for theoretical milk yield  
 240 (MYgap<0), the cow will mobilize body reserve to compensate the MYgap and will  
 241 lose body reserve (if possible). The ability to mobilize will depend on the remaining  
 242 pool of body condition available (**actualBCSpool**) and the stage of lactation with a  
 243 higher ability of the cow to mobilize in early lactation (Faverdin *et al.*, 2010):

$$244 \quad bcsMYresp = MYgap \times \left( 0.75 + 0.25 \times \frac{LacD}{7} \times e^{-0.25 \times \frac{LacD}{7}} \right) \times \frac{actualBCSpool}{theoMOBmax} \quad (7)$$

245 with bcsMYresp being the response in kg of milk, LacD the day in lactation, with this  
 246 response added to the uflMY.

247 After the 12<sup>th</sup> week of lactation the coefficient applied on the  
 248 (actualBCSpool/theoMOBmax) is set at 0.90. This is because, after week 12, the  
 249 model considers the ability to mobilize the residual pool as constant and similar to  
 250 the value obtained in week 12.

251 In a second step, the impact of the protein content of all the feed intake on the milk  
 252 yield response is represented in the model through the equation developed by Vérité  
 253 and Delaby (2000):

$$254 \quad pdiMYresp = -6.25 + \frac{7.55}{1 + 0.21 \times e^{-0.14 \times (PDI/UFLratio - 100)}} \quad (8)$$

255 with pdiMYresp the response in kg of standard milk and PDI/UFLratio equal to  
 256 PDI<sub>int</sub>/UFL<sub>int</sub> if the gap is negative, and is equal to (PDI<sub>int</sub>/UFL<sub>int</sub>)x(uflMY/TheoMY) if  
 257 the gap is positive.

258 Finally, according to the different combinations of milk gap and PDI/UFLratio, there  
 259 are four situations that can occur. Resulting in the MY calculated as:

- 260 ➤ TheoMY+max(bcsMYresp,pdiMYresp) if MYgap>0 and PDI/UFLratio>100,
- 261 ➤ TheoMY+bcsMYresp+pdiMYresp if MYgap>0 and PDI/UFLratio <100,

- 262           ➤  $ufIMY + \max(bcsMYresp, pdiMYresp)$  if  $MYgap < 0$  and  $PDI/UFLratio > 100$ ,
- 263           ➤  $ufIMY + bcsMYresp + pdiMYresp$  if  $MYgap < 0$  and  $PDI/UFLratio < 100$ .

264

265 *BCS change.* The daily change of BCS (**BCSchange**) in units of BCS is dependent  
266 on the UFL balance of the animal meaning the energy differences between UFL  
267 intake and UFL expenditure as milk, maintenance, gestation and growth  
268 (Supplementary Equation S7). If the cow is in a deficit of energy, the loss of BCS will  
269 be calculated as one unit of BCS equal to 250 UFL as described by Jouven *et al.*  
270 (2008) (Supplementary Equation S8). If the cow is in surplus of energy an equation  
271 (Supplementary Equation S10) has been developed to ensure that there is never a  
272 BCS higher than 5. It integrates the higher costs of adipose tissue deposition for a  
273 cow in high condition ( $BCS > 3.5$ ). It is based on a basic cost of 300 UFL for one point  
274 of BCS for a cow between 1.5 and 3.5 of BCS (Jouven *et al.*, 2008). In the model  
275 every day, the BCSpool is calculated as the actual BCSpool from previous day  
276 minus the BCSchange taking into account an upper bound limit of 0 and a lower  
277 bound limit of the theoMOBmax (the theoMOBmax is always negative).

278 When dry, the BCS change is using the same dynamic only with the component  
279 linked to milk set at 0.

280

### 281 *Sensitivity analysis*

282 The model was evaluated by comparing the simulated performance under various  
283 scenarios with data available from the literature. The simulation used scenarios that  
284 systematically varied the following key components:

- 285 (i) Milk production potential: Three different theoretical maximum milk  
286 yields: 30 kg/cow per day (**LG**), 40 kg/cow per day (**MG**) or 50 kg/cow  
287 per day (**HG**).
- 288 (ii) Feed allowance: Three different herbage allowance (**HA**) 14 kg/cow  
289 per day, 18 kg/cow per day and 22 kg/cow per day (all assumed to be  
290 grazed to 4 cm)
- 291 (iii) Supplementation: The addition of 0 or 4 kg of cereal based concentrate  
292 per cow per day throughout the entire lactation

293 This resulted in 18 different scenarios. The simulations were carried out for a full 12  
294 month period (starting on the first of January) allowing the observation of the whole  
295 lactation. It was assumed that at the start of the simulation the parity 3 cows had a  
296 BCS at calving of  $N(3.6,0.25)$ ,  $N(3.4,0.25)$  and  $N(3.2,0.25)$  for the LG, MG and HG  
297 groups, respectively (1 to 5 scale), a BW of 615 kg and that animals were dry and  
298 208 days pregnant. The BCS parameters follow a normal distribution as described  
299 by Geweke (1991):  $N(\text{average}, \text{standard deviation})$ . Feed quality was constant  
300 throughout the simulation and was based on published experiments (grass:  $FV=0.95$   
301  $FU$ ,  $UFL=1.00$ ,  $PDI=103$ ; Concentrate  $UFL=1.10$ ,  $PDI=126$ , silage:  $FV=1.13$ ,  
302  $UFL=0.75$ ,  $PDI=51$ ) (McCarthy *et al.*, 2012) and it was assumed that the cows were  
303 grazing for their whole lactation.

304

### 305 *Model external evaluation*

306 The model was used to simulate two very different experiments, one in Ireland and  
307 one in France. Outputs from the model in relation to milk production and BCS were  
308 evaluated relative to the experimental data. The next section describes the two

309 studies used to complete the evaluation. The description of the experiments has  
310 been confined to the part relevant to this evaluation.

311

312 *On farm studies, Irish experimental study 1 (Curtins experiment).* The first  
313 experimental study has been carried out at the Animal and Grassland Research and  
314 Innovation centre, Teagasc, Moorepark, Ireland (52.17°N; -8.27°W). This experiment  
315 has been previously fully described in McCarthy *et al.* (2013). Two different SR's  
316 have been used to evaluate the model: 3.28 cow/ha (**SR1**) and 2.51 cow/ha (**SR2**).  
317 The cows used in this experiment were based on Holstein Friesian of both North  
318 American and New Zealand origin balanced for overall genetic merit. Concentrate  
319 supplementation was similar for all treatments which started at 4 kg per day post  
320 calving and was reduced and removed totally only when herbage supply exceeded  
321 animal demand for all treatments (usually mid-March). Cows were milked twice a day  
322 and milk yields were recorded individually. Milk fat and protein concentrations were  
323 determined weekly from successive evening and morning milkings. Body condition  
324 score was assessed every three weeks by the same individual throughout the study  
325 on a scale of one to five in increments of 0.25. On the first of January 2009 each SR  
326 group were composed of 31 cows and 15 pregnant heifers. The qualities of the grass  
327 and concentrate from this experiment are presented in Table 1.

328 *Table 1 around here*

329

330 *On farm studies, French experimental study 2 (LePin experiment).* The objective of  
331 this experiment carried out at the INRA experimental farm of Le Pin-au-Haras  
332 (48.448°N, 0.098°E) was to evaluate over an extended period of time the ability of  
333 different breeds of dairy cows to produce and to reproduce under two feeding



334 strategies in the context of group calving. This experiment has previously been fully  
335 described in Cutullic *et al.* (2011). Since 2006, two groups of dairy cows from the  
336 Holstein and the Normande breeds were evaluated under two feeding strategies.  
337 In early lactation during the winter period (90 days), animals of the high feeding  
338 group received an *ab libitum* total mixed ration (TMR) with maize silage (55%),  
339 dehydrated alfalfa (15%) (average forage quality 0.90 FV, 0.89 UFL and 76 PDI) and  
340 30% of concentrate (average concentrate quality 1.1 UFL and 165 PDI per kg DM).  
341 During the same period animals of the low feeding group were fed *ad libitum* with a  
342 TMR composed of grass silage (50%) and haylage (50%) without any concentrate  
343 (average of 1.07 FV, 0.92 UFL and 83 PDI). In early April when at grazing, the high  
344 feeding group of cows had access to a limited grass area of 0.35 ha per cow  
345 (permitting around 90 days of full grazing without forage supplementation) with a  
346 grass quality average of 0.98 FV, 0.91 UFL and 100 PDI. They received 4 kg of  
347 concentrate per day (average of 1.11 UFL and 136 PDI) and as soon as a grass  
348 deficit was detected, 5 to 8 kg of maize silage was added to the diet. The low feeding  
349 group of cows had access to a larger grass area of 0.55 ha per cow (permitting 180  
350 days of exclusive grazing) with a grass quality average of 0.97 FV, 0.89 UFL and  
351 102 PDI. They received no concentrate supplementation. Late in autumn, the grazed  
352 grass was replaced by grass silage (quality of 1.06 FV, 0.98 UFL and 67 PDI).

353

354 *Model evaluation.* In order to make consistent comparisons, the milk produced in the  
355 experiments was transformed into standard milk (Supplementary Equation S12). For  
356 the milk production and body condition score, in both experiments, the model was  
357 evaluated on a weekly time step.

358 The maximum theoretical milk yield for the Irish study was set for all mature cows at  
359 a mean of 37 kg, (SD: 5 kg) of milk per day. This potential was determined by  
360 evaluating the performance of the average actual cows through the 3 years. The  
361 average milk yield of the cattle was adjusted to parity 3 equivalents by assuming that  
362 parity 1 and parity 2 yield were 75 % and 92 % of parity 3 yields (Hutchinson *et al.*,  
363 2013). As the SRs were balanced for milk yield, the same theoMYmax yield has  
364 been applied across SR. Then the level of feeding effect has been included in the  
365 calculations as low (SR2) and very low (SR1) leading to a correction of the potential  
366 of 1.25 and 1.40 respectively compared to the actual milk deliveries. These  
367 corrections were generated based on historical information. For the French study, a  
368 specific genetic index (Delaby *et al.*, 2010b) developed for this study was used to  
369 generate the individual theoMYmax (average of 53 kg, SD of 5 for the Holstein  
370 mature cows, average of 40 kg, SD of 4 for the Normande mature cows). The  
371 genetic index included the sire and grandsire's genetic evaluation, the dam's milk  
372 production over 3 lactations adjusted for the fixed environmental effect and the  
373 feeding treatment applied during each lactation. For the Irish data the prediction of  
374 the model was evaluated by comparing average weekly model outputs of the sub-  
375 cattle versus the experimental data from the first to the 40<sup>th</sup> weeks of lactation. The  
376 simulation was run for both SR's, and results of multiparous and primiparous cows  
377 were evaluated separately.

378 Using the French data the model prediction of the two different breeds and two  
379 different feeding levels was completed by comparing average weekly model outputs  
380 of the groups versus the experimental data from the first to 44<sup>th</sup> week of lactation.  
381 Based on individual genetic information available for the French data, it was possible  
382 to complete individual animal simulations (as it was possible to estimate the

383 theoMYmax) and subsequent evaluation. The comparison between the simulation  
384 and actual data included the individual weekly average milk yield as well as the BCS  
385 for the 3 years. The accuracy of the simulation was evaluated per week and on a  
386 seasonal basis spring (early lactation - week 1 to 15), summer (mid lactation - week  
387 16 to 25) and autumn (late lactation - week > 25).

388

389 *Statistical analyses.* The RMSE, RPE and CCC were used to evaluate accuracy of  
390 the model when compared to the actual data. The RMSE provides information on the  
391 accuracy of the simulation by comparing term by term the actual and predicted data  
392 (Bibby and Toutenburg, 1977). The lower the RMSE is, the more accurate the  
393 simulation. The RPE is an expression of the RMSE as a percentage of the actual  
394 data. According to Fuentes-Pila *et al.* (1996), a RPE lower than 10% indicates a  
395 satisfactory prediction, between 10% and 20% a relatively acceptable prediction, and  
396 an RPE greater than 20% suggests a poor model prediction. In this study, the RMSE  
397 and RPE were used on the comparison of the different sub cattle at the lactation  
398 week scale.

399 The CCC (Lin, 1989, Nickerson, 1997) evaluates the correlation between two  
400 datasets but also the deviation from the 45° line. The strength of agreement is  
401 considered as poor if the CCC is lower than 0.65, moderate if between 0.65 and  
402 0.80, substantial if between 0.80 and 0.90 and almost perfect if greater than 0.90  
403 (McBride, 2005).

404

## 405 **Results**

406

407 *Sensitivity analyses*

408 The results of the sensitivity analyses in terms of milk yield and BCS are presented  
409 in Figure 2 and 3. In the simulations, the average daily milk production was 26.4 kg  
410 per cow across all simulations (HA, concentrate and theoMYmax). The highest  
411 average simulated milk yield corresponded to 33.3 kg per cow under the 50  
412 theoMYmax, HA of 22 kg/cow and 4 kg of concentrate with the lowest average milk  
413 yield simulated corresponding to 20.1 kg for the 30 theoMYmax, HA of 14, without  
414 concentrate supplementation. An increase of 1 kg of theoMYmax resulted in an  
415 average increase of 0.4 kg of milk produced. An increase of 1 kg of HA resulted in an  
416 average increase of 0.2 kg of milk per cow per day (minimum of 0.1, maximum of  
417 0.5) which was higher for the 50 theoMYmax cow (average of 0.3 kg) than for the 30  
418 theoMYmax (average of 0.1 kg). An increase of 1 kg concentrate resulted in an  
419 average increase of 0.8 kg of milk per cow per day (maximum of 1.1 kg minimum of  
420 0.5 kg) with this increase being higher for the 50 theoMYmax cow (average of 0.9  
421 kg) than for the 30 theoMYmax (average of 0.6 kg). Furthermore this increase was  
422 higher at an HA of 14 (average of 0.9 kg) than at an HA of 22 (average of 0.6 kg).

423 *Figure 2 and 3 around here*

424

425 The average BCS loss was of 0.63 units between calving and nadir, with a maximum  
426 loss of 1.1 for the 50 theoMYmax, HA 14 kg with no concentrate and a minimal loss  
427 of 0.2 units for the 30 theoMYmax, HA 22, 4 kg of concentrate. The impact of an  
428 increase of 1 kg in theoMYmax resulted in an average increase in BCS loss of 0.03  
429 units of BCS to the nadir. The impact of an increase of 1 kg of HA resulted in an  
430 average decrease of 0.01 units of BCS loss to the nadir. In terms of concentrate the  
431 increase of 1 kg of concentrate resulted in an average decrease of BCS loss of 0.05  
432 units.

433

434 *Curtins experiment*

435 *Model outputs.* The model simulated a higher daily (1.3 kg of milk per cow) and  
436 annual (893 kg of milk per cow) milk production for the multiparous cows managed  
437 under the SR2 treatment than under the SR1 (Table 2). The same trend was  
438 observed for the primiparous cows with an average increase of daily production of  
439 1.8 kg per cow and an average increase of 907 kg of milk through the whole lactation  
440 from the SR1 to the SR2 treatment. For the BCS the model simulated a higher  
441 average BCS throughout lactation for the SR2 than for the SR1 (0.15 units higher for  
442 the multiparous and 0.05 higher for the primiparous) (Table 2). The model simulated  
443 a higher average BCS for the primiparous cows than for the multiparous cows  
444 (average of 3.03 against 2.87). The BCS loss across the different stocking rates was  
445 similar with 0.47 and 0.44 for the SR1 and SR2 respectively (average between  
446 primiparous and multiparous).

447 *Table 2 around here*

448

449 *Model evaluation.* Over the total lactation, the weekly milk production for the SR1  
450 group of cows had an RPE of 6.97% for the multiparous cows and 11.86% for the  
451 primiparous cows (Table 2) when the model outputs and the experimental data were  
452 compared. The higher RPE for the primiparous cows was related to an  
453 underestimation of the milk production of these group of cows in the spring  
454 (RPE=13% and RMSE=2.58 kg) and a slight underestimation of the milk production  
455 in autumn (RPE=10% and RMSE=1.32 kg). For both primiparous and multiparous  
456 cows in SR1, the BCS through lactation and per season resulted in an RPE which  
457 was lower than 4% and the RMSE lower than 0.10 units of BCS (Table 2). The

458 weekly milk production of the SR2 group of cows was reasonable with the RPE  
459 throughout lactation and at a seasonal level lower than 8% for both multiparous and  
460 primiparous SR2 cows (Table 2). On the cumulative milk yield the primiparous SR2  
461 cows had a RPE of 2% and RMSE of 115 kg of milk. For the multiparous cows, the  
462 model overestimated the milk yield with an RPE of 11% and a RMSE of 680 kg. The  
463 difference in percentage of error between the weekly milk yield and the cumulative  
464 milk yield is due to the difference in the lactation length between actual and  
465 predicted. The BCS of the SR2 animals resulted in an RPE which was less than 5%  
466 with the RMSE lower than 0.15 units (Table 2).

467 The accuracy of the model was similar for both SR's, however there was a decrease  
468 in precision in the model for the primiparous cows in the SR1 groups.

469

#### 470 *Le Pin experiment*

471 *Model output.* The model simulated a higher average milk production for the high  
472 feeding group (average of 25.7 kg of milk per cow per day) of cows than for the low  
473 feeding group of cows (average of 20.3 kg of milk) and a higher milk production for  
474 the Holstein cows (average of 24.7 kg of milk) over the Normande cows (average of  
475 21.3 kg of milk) (Table 3). On average through the overall lactation the high feeding  
476 group of cows produced 1 935 and 1 486 kg per cow more milk than the low feeding  
477 group for the Holstein and the Normande groups of cows, respectively (Table 3). The  
478 model simulated a higher BCS loss for the Holstein than for the Normande (average  
479 of 0.89 against 0.64) group and a slightly higher loss for the low feeding group than  
480 for the high feeding group (average of 0.85 against 0.68).

481 *Table 3 around here.*

482

483 *Model evaluation.* For the high feeding group, the weekly milk production had an  
484 RPE which was less than 10% at both overall lactation and seasonal scale for both  
485 Holstein and Normande cows (Table 3). For the average BCS the model had an  
486 RPE which was less than 10% with all computed RMSE figures lower than 0.25 units  
487 for the high feeding group of cows (Table 3). The differences between the actual and  
488 the predicted BCS loss were 0.06 for the Holstein and 0.14 for the Normande cows.  
489 For the cows in the low feeding systems when compared on a weekly basis, all RPE  
490 values were less than 15% for milk yield (Table 3). The model has a tendency to  
491 slightly overestimate the milk production for both Holstein and Normande cows in the  
492 low feeding systems in summer (RPE of 14% and 11%, RMSE of 2.73 kg/cow per  
493 day and 1.95 kg/cow per day respectively) and autumn (RPE of 14% and 12%,  
494 RMSE of 2.35 kg/cow per day and 1.74 kg/cow per day). For the average BCS the  
495 prediction were relatively accurate with all RPE values less than 15% and all RMSE  
496 values less than 0.25 units except for the low feeding Holsteins in autumn (RMSE of  
497 0.27) (Table 3). The differences between the actual and predicted BCS loss are 0.02  
498 for the Holstein and 0.16 for the Normande groups.  
499 The model has been more accurate in simulating the high feeding levels than the low  
500 in terms of milk production due to an over prediction of the milk production of the low  
501 feeding group in autumn. In terms of BCS the model was slightly more accurate in  
502 predicting the BCS of the Holstein than the Normande cows due to an  
503 underestimation of the BCS of the Normande group.  
504 As the genetics of the individual cows was available, a comparison at individual cow  
505 level was also completed for both breed and feeding systems together. For the total  
506 milk production throughout lactation the CCC was 0.85 with a coefficient of bias of

507 0.97 (Figure 4). On the comparison by week of lactation the CCC was 0.84 with a  
508 coefficient of bias of 0.99.

509 *Figure 4 around here*

510

## 511 **Discussion**

512

### 513 *Overall assessment of the model*

514 The model developed in this study has been able to react in a sensible fashion to  
515 variation in concentrate feed levels, herbage allowance and herd genetic potential.  
516 Using the French data, the model was capable of reproducing the impact of the  
517 different types of feeding (high and low feeding group) as well as the different types  
518 of feeding intra group (TMR, grazing and indoor feeding). The model was also  
519 capable of reproducing the higher milk production and BCS loss of the Holstein cows  
520 when compared to the Normande cows. For the Irish data, the model was capable of  
521 adapting to the two different stocking rates by simulating higher average milk yields  
522 per cow for the lower stocking rates showing the ability of the model to react  
523 realistically to variation in feed levels. Primiparous cows have also produced  
524 significantly less milk than the multiparous cows in the simulation.

525 In relation to herbage allowance and concentrate feed level variation, the model  
526 responses are within the range of previously published studies. In this model the  
527 impact of theoretical milk is higher in early lactation (between 4.2 to 6.0 kg of  
528 standard milk per 10 kg of theoretical milk) than in late lactation (between 3.0 to 3.9  
529 kg of standard milk). This finding is in agreement with the findings of Buckley *et al.*  
530 (2000) which showed that a higher peak milk yield is associated with a steeper  
531 decline (less persistent) lactation curves, which leads to a decrease of the impact of



532 genetic potential in late lactation. The outputs from the model show an overall trend  
533 that is similar to previous studies with a change from 0.08 to 0.45 kg of milk per  
534 kilogram of HA simulated in the model. This compares to 0.02 to 0.23 kg of milk per  
535 kg of herbage allowance in the literature. As shown in previous studies, the  
536 concentrate response increased with the theoretical milk production (Fulkerson *et al.*,  
537 2008) and it decreased with increasing HA (McEvoy *et al.*, 2008). The outcomes  
538 from this model are within the range of the previously published studies for  
539 concentrate supplementation (Supplementary Table S5) with the impact of 1 kg of  
540 concentrate resulting in an increase of 0.5 to 1.1 kg of standard milk across different  
541 genotypes and HA categories. The impact of concentrate supplementation on body  
542 condition score loss has been demonstrated by the model. The impact of the  
543 increase of 4 kg of concentrate per cow per day resulted in a reduction in the body  
544 condition loss post calving, this impact is higher for the LG and MG (0.21 units) than  
545 for the HG cow (0.16 units). The model outputs are within the range of previously  
546 published studies with a reduction of BCS loss of between 0.03 and 0.05 of BCS per  
547 kg of concentrate (Horan *et al.*, 2005, McCarthy *et al.*, 2007).

548

#### 549 *External evaluation*

550 With an RPE lower than 15% the model can be said to have good accuracies at  
551 predicting BCS and milk production (Fuentes-Pila *et al.*, 1996) and is in the range of  
552 previous studies. At the herd level, Baudracco *et al.* (2013) presented a model with  
553 an RPE of 8.8% for annual milk yield. When compared against 206 experiments, the  
554 GrazIN model had an average RPE of 14% at the herd level (Delagarde *et al.*,  
555 2011b). Primiparous cows in the GrazIN model had a higher RPE (19%) than for  
556 multiparous cow (11%) (Faverdin *et al.*, 2011). At individual animal level Baudracco  
557 *et al.* (2013) predicted the milk yield with a CCC 0.74 and 0.77 with observed milk

558 yields for two different cow breeds. When taking all of these components together,  
559 this model can be said to be as least as good or better across a range of different  
560 evaluation criteria.

561 For the Irish data, the model developed in this study had a satisfactory prediction for  
562 milk yield on the overall lactation for both stocking rates. However there were some  
563 points of discrepancy. The underestimation of the model in early lactation of the  
564 primiparous SR1 cows shows that the model underestimates the ability of the  
565 primiparous cows to compensate for the lack of feed despite a relatively accurate  
566 prediction of the BCS. The prediction of BCS change is very accurate for the Irish  
567 data with all RPE lower than 5% at the lactation or season levels. Within the French  
568 data all RPE were lower than 15% for daily milk production over the lactation which  
569 shows that the model is well able to adapt to the different types of feeding (TMR,  
570 grazing, indoor feeding). The model had a tendency to slightly overestimate the milk  
571 production for the Normande dairy cows in early lactation probably due to the over  
572 mobilisation of BCS by the simulated Normande group compared to the actual cows.  
573 For both experiments the model predicted the BCS loss and the nadir with precision  
574 lower than 0.25 which shows a very good accuracy.

575 With respect to fitting individual cow data, the CCC of 0.84 with a coefficient of bias  
576 of 0.99 for weekly milk production and 0.85 with a coefficient of bias of 0.97 for  
577 annual total milk yield, for individual French cows shows that the model is well able  
578 to predict at animal level the impact of feeding and individual animal genetics on  
579 individual milk yields. However, a good and precise definition of the theoretical milk  
580 yield of the cow is needed for accurate simulations. This highlights the need to  
581 develop tools for estimating theoMYmax in the field to allow for a precise simulation  
582 in the model as the results are sensitive to both theoretical maximum milk and BCS

583 at calving. Finding an accurate theoretical maximum milk yield for the dairy cow is  
584 always a challenge as the cows are almost never fed enough to express their full  
585 potential (Faverdin *et al.*, 2010) When the model will be ready for commercial farms  
586 use, a feature will be added to permit the calculation of the theoMYmax using  
587 genetic information and historical information.

588

### 589 *Model advancement and limitations*

590 The HDM model is an individual-based model focusing principally on the impact of  
591 diet and management on milk production and BCS at individual animal and herd  
592 level. Many models have been developed to simulate the production of cattle at  
593 grazing but there are varying levels of accuracy and many do not permit the  
594 modelling of individual existing animal performance. For example, in the model e-  
595 Dairy (Baudracco *et al.*, 2013), which is an individual-based model, each cow is  
596 generated randomly at the start of the simulation (for the potential milk yield and the  
597 body weight at calving). Contrary to the HDM model, the duration of the simulation is  
598 fixed at one year, not allowing the testing of longer term strategies. As in the HDM  
599 model the individual and herd milk production, BCS and BW are simulated daily but  
600 in addition the daily protein and fat content is also simulated in the e-Dairy model.  
601 Models like the one described by Rotz *et al.* (1999) use groups of animals (early mid  
602 and late lactation sub divided with multiparous and primiparous cows) to simulate the  
603 milk production and BW. Each group has a potential milk yield, a milk fat content,  
604 BW, change in BW and a fibre digestive capacity. Once again contrary to the HDM,  
605 simulation of a specific animal is not possible neither is the individual simulation of  
606 different management regimes of the cow by her genetic potential. A limitation of the  
607 model is the use of the theoMYmax. The determination of theoMYmax at the farm

608 level is challenging. Research is on-going to link the genetics of the animal to this  
609 theoMYmax to permit an accurate use of the model on farm.

610 The strength of the current model is its ability to balance energy partition between  
611 milk and body reserves according to the gap between intake and requirement.  
612 According to (Martin and Sauvant, 2010b) this allows the model to simulate across a  
613 wide range of genotypes and environments. The model can be defined as efficient in  
614 recreating different extensive grazing scenarios with different animal genetics.  
615 However, further evaluation would be needed if the model would be used for high  
616 genetic merit cows in terms of milk production or very intensive systems with high  
617 levels of concentrate supplementation. The HDM model can be used as the animal  
618 core of a farm systems model (Ruelle *et al.*, 2015) for both research and extension.  
619 This model combined with the system model (the Pasture Based Herd Dynamic  
620 Model) (Ruelle *et al.*, 2015) will be adapted as an online tool to facilitate its use by  
621 farmers and advisors in the future. From a farmer's perspective the combined model  
622 will be used to support the decision making process regarding SR, preGH, postGH  
623 and concentrate supplementation. However, the HDM model only simulates a cow in  
624 what could be described as good health status and does not take into account the  
625 possible impact of mastitis, lameness or other health related events, which would  
626 require further development.

627

## 628 **Conclusion**

629 The model presented is capable of adapting to different management systems and  
630 animal breeds in a realistic manner when compared to already published  
631 experiments and experimental data with all RPE lower than 15% for both BCS and  
632 milk production. The model simulates milk production and BCS of the Holstein dairy

633 cows at grazing as well as in indoor feeding situations accurately. The model is well  
634 able to simulate the effects of stocking rate in grass based systems for both  
635 multiparous and primiparous cows. However, there is a requirement for more work in  
636 relation to body condition score for the Normande breed.

637

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774

775 **Table 1** Information about the quality of the feedstuff by season for the 3 years of the  
776 simulation for the dairy lactating cow on the Irish experiment

777

	FV <sup>1</sup>	UFL <sup>2</sup>	PDI <sup>3</sup>
Spring forage	0.95	1,00	103
Summer forage	0.97	0.98	99
Autumn forage	0.98	0.95	98
Concentrate	-	1.09	103

778 <sup>1</sup>Fill Value

779 <sup>2</sup>Energetic value: "Unité Fourragère Lait" (UFL). 1 UFL = 1700kcal NEL (net energy for lactation)

780 <sup>3</sup>Proteic value: "Intestinal digestible protein"

781

782

783

784 **Table 2** Comparison between the average actual (A) and simulated (S)  
785 standard milk production (kg) and BCS (units) of the dairy cattle for the  
786 stocking rate 3.28 (SR1) and 2.51 (SR2) for the multiparous (M) and  
787 primiparous (P) cow on the Irish experiment

	Lactation week	SR1				SR2			
		Mean A	Mean S	RMSE <sup>1</sup>	RPE <sup>2</sup> (%)	Mean A	Mean S	RMSE <sup>1</sup>	RPE <sup>2</sup> (%)
M I L K	Total milk yield	5336	5916	580	10.86	6129	6809	680	11.10
	1-40	20.7	21.4	1.4	6.97	22.5	22.7	1.5	6.64
	1-16	25.5	25.6	1.7	6.57	26.9	27.5	2.0	7.50
	17-25	20.2	21.8	1.6	7.94	22.5	23.3	1.1	4.80
	26-40	16.0	16.8	1.0	6.11	17.9	17.4	0.9	5.10
	Max milk yield	28.3	28.5			29.9	30.4		
P	Total milk yield	4613	4397	225	4.87	5419	5304	115	2.12
	1-40	16.0	15.7	1.9	11.86	17.5	17.5	0.9	5.07
	1-16	19.5	17.2	2.6	13.22	19.6	19.0	1.1	5.46
	17-25	15.4	15.9	1.0	6.62	17.6	18.2	0.8	4.39
	26-40	12.7	13.9	1.3	10.40	15.2	15.4	0.7	4.31
	Max milk yield	21.2	19.1			21.6	20.6		
B C S	1-40	2.82	2.79	0.07	2.36	2.97	2.94	0.12	4.12
	1-16	2.86	2.81	0.06	2.16	2.99	2.91	0.10	3.34
	17-25	2.72	2.69	0.06	2.11	2.95	2.82	0.14	4.69
	26-40	2.82	2.84	0.07	2.33	2.97	3.04	0.12	4.03
	nadir	2.67	2.70			2.92	2.78		
	BCS loss	0.50	0.48			0.33	0.45		
	1-40	2.95	3.00	0.07	2.54	3.05	3.05	0.06	2.03
	2-16	3.08	3.08	0.03	1.13	3.14	3.12	0.05	1.50
	17-25	2.87	2.93	0.07	2.47	2.99	2.97	0.05	1.56
	26-40	2.85	2.95	0.10	3.55	2.98	3.03	0.07	2.51
nadir	2.80	2.93			2.94	2.96			
BCS loss	0.63	0.45			0.51	0.43			

788 <sup>1</sup>RMSE: root mean square error

789 <sup>2</sup>RPE: relative prediction error

790

791 **Table 3** Comparison between the average actual (A) and simulated (S)  
792 standard milk production (kg) and BCS (units) of the dairy cattle for the high  
793 and low feeding system for the Holstein (H) and Normande (N) cow on the  
794 French experiment

	Lactation week	High				Low			
		Mean A	Mean S	RMSE <sup>1</sup>	RPE <sup>2</sup> (%)	Mean A	Mean S	RMSE <sup>1</sup>	RPE <sup>2</sup> (%)
M I L K	Total milk	8348	8359	11	0.13	6170	6424	254	4.11
	1-44	27.3	27.8	1.6	5.81	20.2	21.6	2.1	10.58
	1-16	34.2	34.7	1.8	5.24	24.8	24.5	1.3	5.32
	H 17-25	25.9	27.8	1.9	7.48	19.9	22.6	2.7	13.75
	26-44	22.2	21.9	1.2	5.19	16.4	18.6	2.4	14.38
	Max milk yield	37.8	38.3			28.8	26.8		
B C S	Total milk	6776	7030	254	3.37	5278	5544	266	5.05
	1-44	22.4	23.6	1.7	7.59	17.6	18.9	1.6	8.86
	1-16	27.9	29.4	2.3	8.15	21.1	21.7	1.0	4.61
	N 17-25	22.0	24.0	2.0	9.12	18.4	20.3	2.0	10.56
	26-44	18.1	18.5	0.7	3.69	14.3	16.0	1.7	12.20
	Max milk yield	30.1	32.7			22.5	23.7		
B C S	1-44	2.45	2.28	0.18	7.53	1.83	1.66	0.20	10.73
	1-16	2.53	2.40	0.15	5.73	1.87	1.82	0.06	3.27
	17-25	2.27	2.09	0.18	7.92	1.72	1.56	0.17	9.89
	H 26-44	2.48	2.27	0.21	8.58	1.84	1.57	0.27	14.60
	Nadir	2.23	2.08			1.64	1.54		
	BCS loss	0.79	0.85			0.90	0.92		
	1-44	3.31	3.14	0.18	5.35	2.69	2.48	0.22	8.05
	1-16	3.29	3.15	0.15	4.53	2.78	2.60	0.18	6.39
	17-25	3.20	2.97	0.23	7.13	2.60	2.36	0.24	9.17
	N 26-44	3.37	3.22	0.17	5.05	2.66	2.44	0.23	8.83
Nadir	3.17	2.96			2.58	2.35			
BCS loss	0.36	0.5			0.62	0.78			

795

796 <sup>1</sup>RMSE: root mean square error

797 <sup>2</sup>RPE: relative prediction error

798 **Figure captions**

799

800 **Figure 1** Flow diagram representing the running of the model to predict the  
801 real milk yield of an animal.

802

803 **Figure 2** Influence of the genetic milk potential of the cow (a: 30kg, b: 40kg,  
804 c: 50kg), the herbage allowance per cow (grey dot: 14; black dot: 18, black  
805 line: 22) and the amount of concentrate per cow per day (thin line:0, bold line  
806 4) on average standard milk yield (kg) of a dairy herd

807

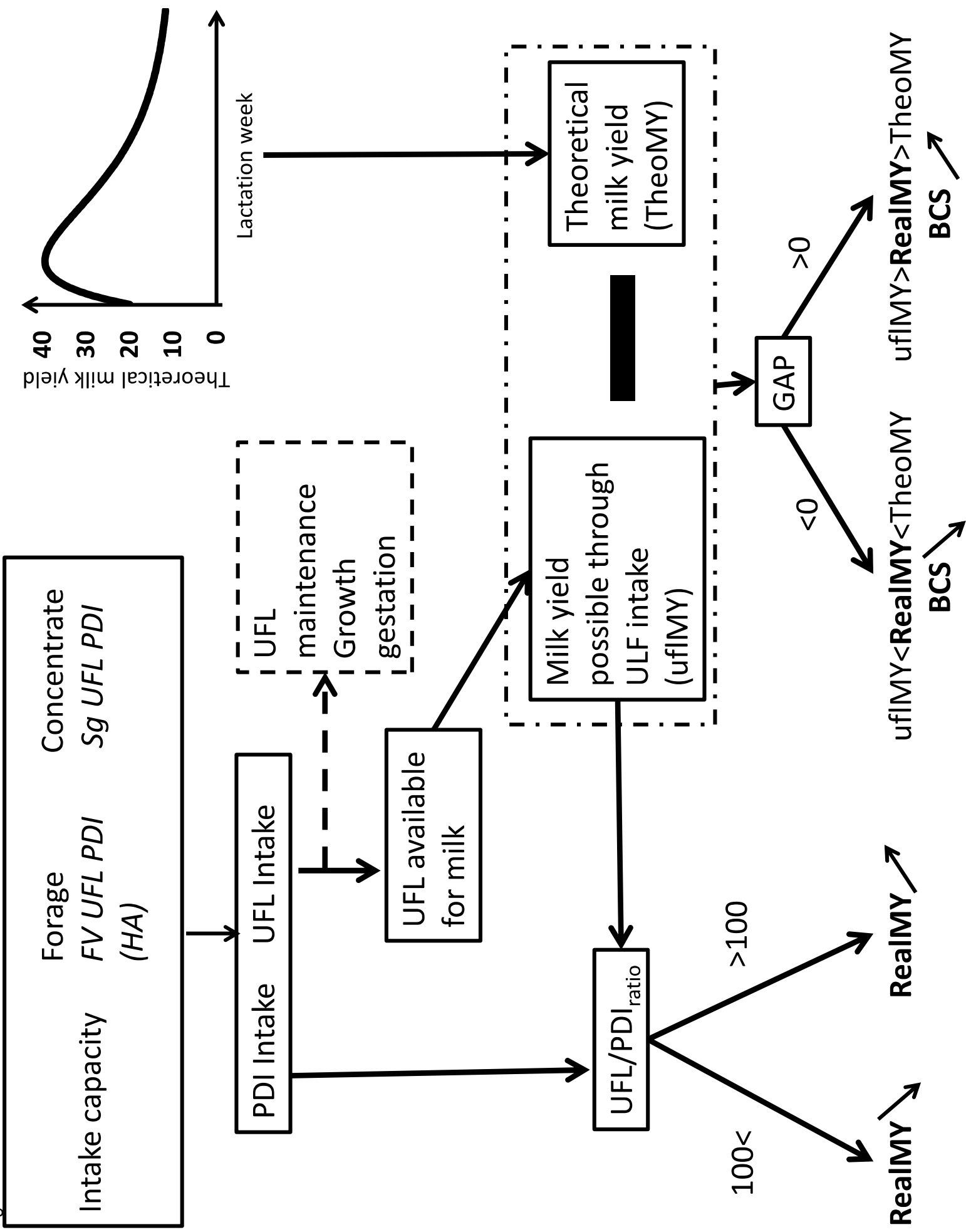
808 **Figure 3** Influence of the genetic milk potential of the cow (a: 30kg, b: 40kg, c:  
809 50kg), the herbage allowance per cow (grey dot: 14; black dot: 18, black line:  
810 22) and the amount of concentrate per cow per day (thin line:0, bold line 4) on  
811 average body condition score (1-5) of a dairy herd

812

813 **Figure 4** Comparison between the individual actual and predicted total  
814 lactation standard milk yield of the French cows. One dot represents the  
815 global milk production of one cow through one lactation. The full dot represent  
816 the high feeding level, empty dot the low feeding level, the round dot the  
817 Holstein cows and the square dot the Normande cows.

818

Figure 1



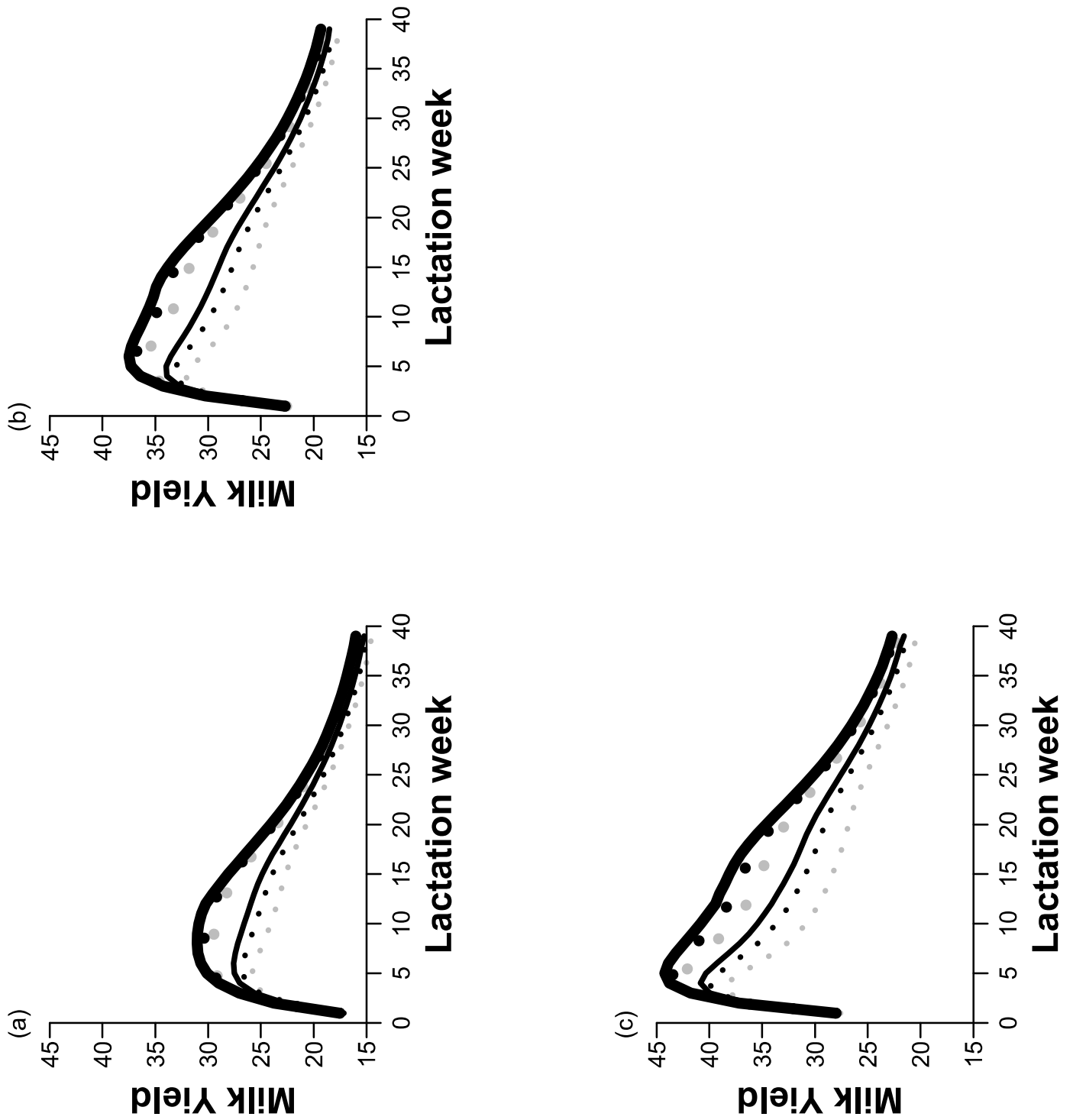
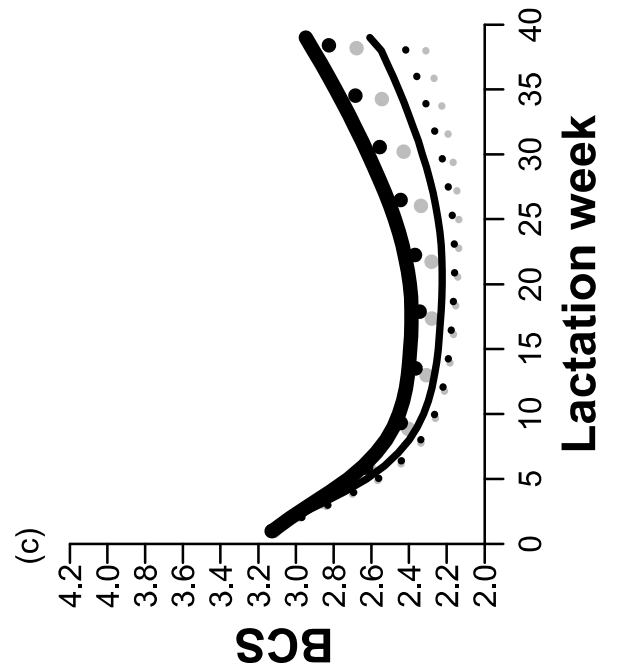
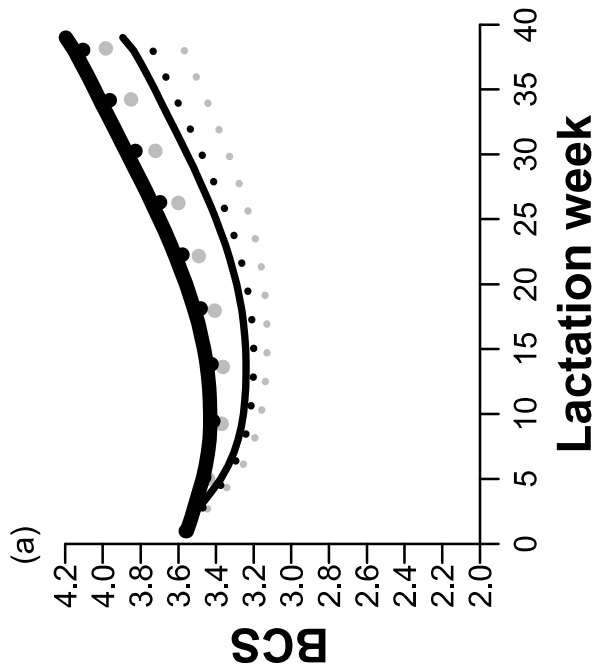
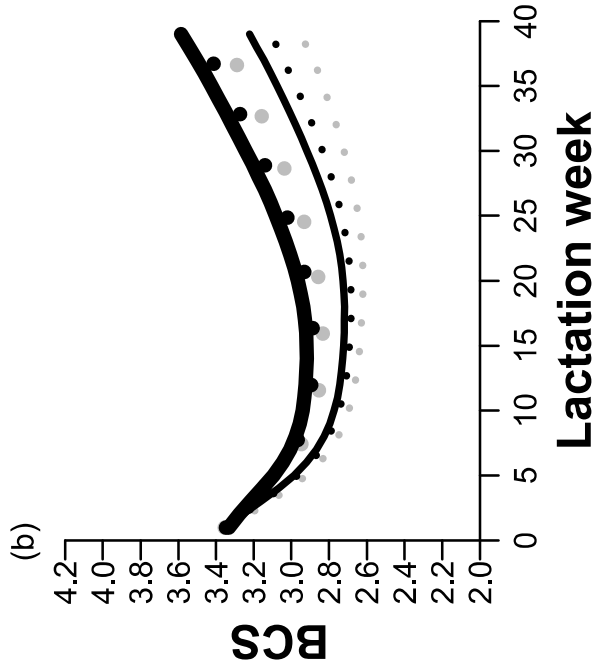


Figure 2





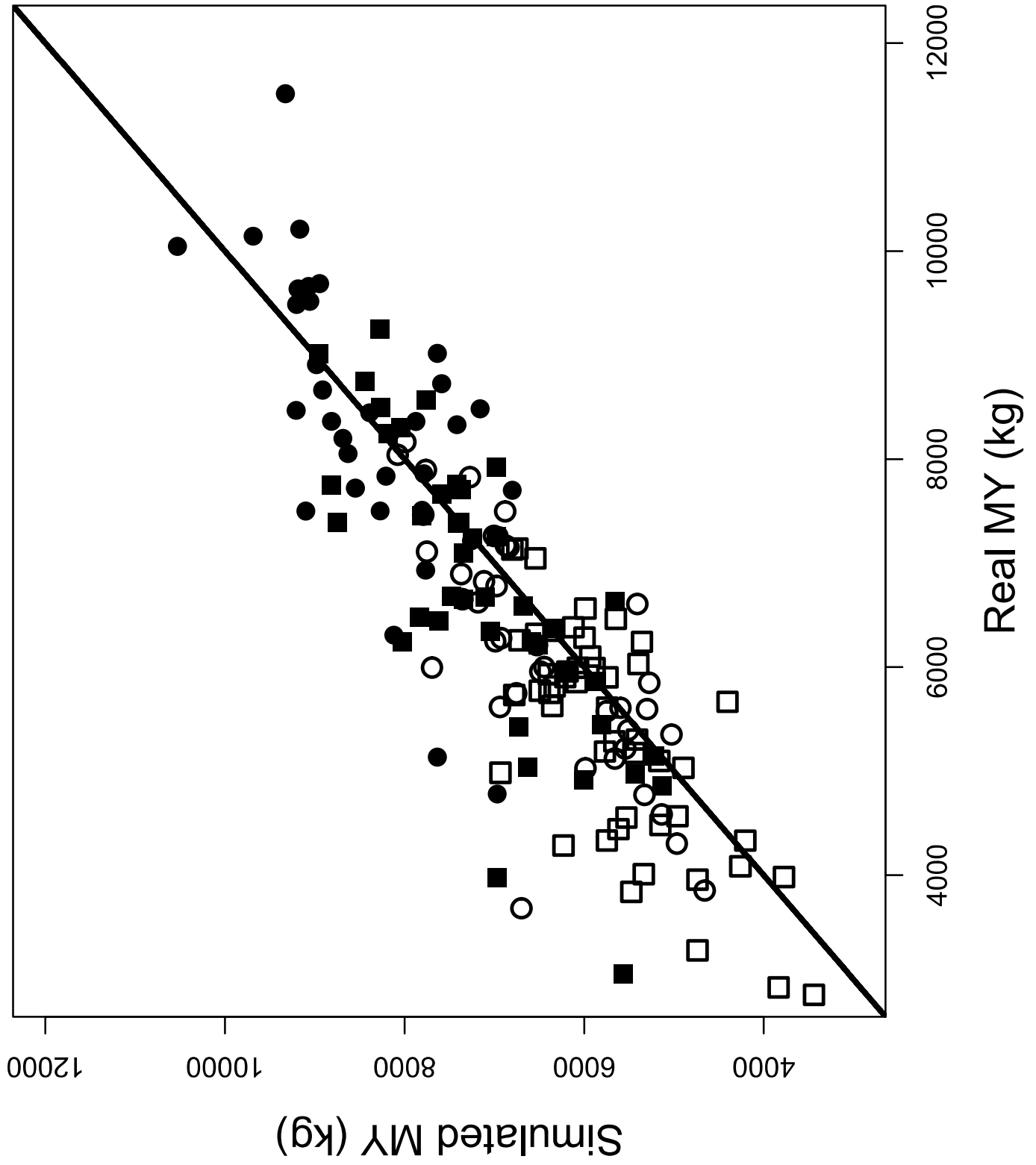


Figure 4

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## Development and evaluation of the herd dynamic milk (HDM) model with focus on the individual cow component

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### Supplementary Material S1: Feeding, bcs change and milk production of the dairy cow

The intake and the requirement of the animal is based on the model GrazeIN all the equation and justification are described in (Delagarde *et al.*, 2011a, Delagarde *et al.*, 2011b, Faverdin *et al.*, 2011). The calculation of the intake and intake at grazing is fully describe in (Delagarde *et al.*, 2011a, Faverdin *et al.*, 2011) and won't be re describe here. The only differences are that the MP<sub>prot</sub> (equation 20 is (Faverdin *et al.*, 2011)) is replaced by the TheoMY (equation X and Y) and that the UFL<sub>mob</sub> (equation 19 in (Faverdin *et al.*, 2011)) is replaced by the actual BCS<sub>loss</sub> of the previous day in the HDM.

#### *Requirement of the animal*

Supplementary Equation S1:  $UFL_{req} = GrowthReq + GestReq + MaintReq$

Supplementary Equation S2:  $GrowthReq = 3.25 - 0.08 \times Age$

with Age in months,

Supplementary Equation S3:  $GestReq = 0.00072 \times BW_{calf} \times e^{\frac{0.116 \times GestD}{7}}$

With  $BW_{calf}$  the BW of the calf at birth and GestD the day in gestation of the cow

(Linked with the Gest requirement the BW of the cow increase of GestReq/4.5)

Supplementary Equation S4:  $MaintReq = (0.041 \times BW^{0.75}) \times Coeff_{req}$

with Coeff<sub>req</sub> equal to 1.2 at grazing and 1.1 for indoor feeding (Faverdin *et al.*, 2010).

#### *Energetic interaction:*

Supplementary Equation S5:  $E = 6.3 \times \%C^2 - 0.017 \times UFL_{int} + 0.002 \times UFLing_{int}^2$

with %C the percentage of concentrate in the diet and UFL<sub>int</sub> the quantity of UFL ingested during the day in UFL.

Grummer *et al.* (1995) has shown that for the first eight weeks of the lactation for a primiparous cow, growth rate is substantially reduced with most of the energy consumed directed toward milk production. Taking this into account, it has been assumed that during the eight first weeks of lactation, the growth of the younger cow

slows down, therefore, there is a requirement for a coefficient to be multiplied to the growth requirement of the animal:

$$\text{Supplementary Equation S6: } \textit{growth\_coefficient} = \frac{\textit{nb\_day\_in\_milk}}{7 \times 8}$$

with *nb\_day\_in\_milk* the number of days in milk of the cow, 7 the number of days per week and 8 the eight weeks involved in the reduction of the growth rate.

*UFL balance:*

Supplementary Equation S7:

$$\textit{UFLbalance} = 0.3 \times \textit{UFLint}_{D-2} + 0.7 \times \textit{UFLint}_{D-1} - (\textit{UFL\_Req} + \textit{MY} \times 0.44) - E$$

If the cows are dry the UFL balance is calculated with a MY equal to 0, the requirement due to milk is set at 0.

*BW and BCS change in case of negative energy balance:*

$$\text{Supplementary Equation S8: } \textit{BCSchange} = \frac{\textit{UFLbalance}}{250}$$

$$\text{Supplementary Equation S9: } \textit{BWchange} = \frac{\textit{UFLbalance}}{3.5}$$

With the BCSchange in unit of BCS.

*BW and BCS change in case of positive energy balance:*

$$\text{Supplementary Equation S10: } \textit{BCSchange} = \textit{UFLbalance} \times \left( 0.0034 - \frac{0.000004}{e^{-1.325 \times \textit{BCS}}} \right)$$

$$\text{Supplementary Equation S11: } \textit{BWchange} = \frac{\textit{UFLbalance}}{4.5}$$

For every day, the BCSpool is calculated as the actual BCSpool from previous day minus the BCSchange taking into account an upper bound limit of 0 and a lower bound limit of the *theoMOBmax* (the *theoMOBmax* is always negative).

Equation to go from actual milk yield to standard milk yield:

Supplementary Equation S12: (Faverdin *et al.*, 2010)

$$\textit{MY} = \frac{\textit{actualMY} \times (0.44 + 0.0055 \times (\textit{FC} - 40) + 0.0033 \times (\textit{PC} - 31))}{0.44}$$

with *actualMY* the non corrected milk yield in kg, FC and PC the fat and protein content in gram per kg of non corrected milk.

## Supplementary Material S2: Fertility calculation

Interval between two heat event:  $N(22.75, 3.17)$  (Brun-Lafleur, 2011)

Calculation of the return in heat:

$N(47.9 - 5.7 * (2.63 - BC_{Scalv}), 27.4)$  days after calving (Pryce *et al.*, 2001)

The percentage of foetal death is set at 3% (abortion) (Brun-Lafleur *et al.*, 2013) the rate of late embryonic death is set at 20% (Cutullic *et al.*, 2011).

*Supplementary Table 1: Description of the different percentage and coefficient used to calculate the percentage of change of recalving (RC) after artificial insemination (AI) for the dairy cow (taking into account the fact that to be inseminated the farmer need to have seen that the cow was in heat its depending on the heat detection level which is an input)*

	Description	percentage	modification	reference
First AI RC	Basic percentage for parity 1 to 3	44		(Inchaisri <i>et al.</i> , 2010)
	parity bigger than 3	39		
	parity 2 and 3 inseminate between DIM 40-60	39		
	parity bigger than 3 between DIM 40-60	31		
other AI RC	basic percentage	42 to 49		(Dillon <i>et al.</i> , 2003, Inchaisri <i>et al.</i> , 2010)
Overall	occur between DIM 21 and 40		x 2/3	(McDougall <i>et al.</i> , 2012)
	occur before DIM 21		x 1/2	
	last calving ease of 3 non Holstein cow		x 0.64	
			+10%	

## Supplementary Material S3: Calving calculation:

Percentage of chance to have twin: 1% for parity 1, 3.8% for parity 2, 4.9 for parity 3 and more.

*Supplementary Table S2: Percentage of the different calving ease score depending on cow and calf parameters (Lombard *et al.*, 2007, Mee *et al.*, 2011):*

	1	2	3
Parity 1	48.8%	32.3%	18.9%
Parity 2	70.6%	22.5%	6.9%
Single calf	65.9%	23.4%	10.7%
Twin	44.3%	44.3%	12.4%
Female calf	67%	24.8%	8.2%
Male calf	60%	26.5%	13.4%

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Furthermore, if the previous calving had a calving ease score of 3 the probability of a score of 1 is unchanged the probability of a score of 2 is multiplied by 1.65 the probability of a score of 3 is multiplied by 2.9 (the actual percentage are recalculated after).

#### Supplementary Material S4: Creation of the new calf

BW of the calf at calving (consider that the BW of the calf at calving will depend on the sum of the gestation requirement during the year with an average calf weight at calving of 42):

$$\text{Supplementary Equation S13: base} = \frac{\sum_{k=0}^{DIG} 0.00072 \times 42 \times e^{0.116 \times \frac{k}{7}}}{4.5}$$

if it's a heifer the base is reduce of 5 kg.

If there is twin the base is reduce of 5.

Finally the BW of the calf at calving will be:  $BW = N(\text{base}, 1) - 5$

The BW of the cow is changed in accordance by deleting twice the BW of the calf (only 1.5 if it's twins).

The calf genetic index is calculated as it's mother genetic index multiply by 1.02 plus  $N(0,1)$ .

#### Supplementary Material S5: Death of the animals

The basic percentage of stillbirth is set at 2 (can be changed). This percentage is multiply by 1.7 for a primiparous cow, by 2.3 if the calving ease score is 2, 15.4 if the calving ease score is 3, 2.7 if there is twin, 1.4 if the calf is a male (Lombard *et al.*, 2007).

*Supplementary Table S3: Annual probability of death depending on the parity (Miller et al., 2008):*

Parity	1	2	3	4	5	6	7	8+
Base % death	2.05	2.66	3.72	4.38	4.83	5.78	5.92	6.40

*Supplementary Table S4: Multiplicatif coefficient for the probability of death depending on the month of the year (Miller et al., 2008):*

Month	1	2	3	4	5	6	7	8	9	10	11	12
coeff	1.00	1.10	1.07	0.99	0.95	0.95	1.05	1.13	1.01	0.90	0.89	0.98

Coefficient multiplied by 1.81 if the last calving ease was of 3.

Those coefficients are the annual percentage of death. It is considered that half of the “chances” occur the day of calving.

### Supplementary Material S5: Calf and heifer feeding and growing

The hypothesis is made that the calf (0 to 91 days) are growing of 600g per day.

The intake capacity of the heifer (IC) is calculated as (Agabriel and Meschy, 2010):

$$\text{Supplementary Equation S14: } IC = 0.035 * BW^{0.9}$$

Calculation of the actual forage intake (iterative process) for more information/explanation (Agabriel and Meschy, 2010):

$$\text{Supplementary Equation S15: } A = 1 - (1.26 \times (avFVfor - 0.85))^{0.84}$$

With avFVfor the average fill value of the forage intake

$$\text{Supplementary Equation S16: } D = \frac{1}{avFVfor} - A$$

$$\text{Supplementary Equation S17: } B = \frac{avFVfor}{2.04 \times D}$$

$$\text{Supplementary Equation S18: } K = avFVfor \times D \times e^{\frac{B}{0.7}}$$

$$\text{Supplementary Equation S19: } Sg = \frac{0.86}{avFVfor} \times \left(1 - K \times e^{\frac{-B}{1-\%C}}\right)$$

Sg: the concentrate substitution rate

%C percentage of concentrate (between 0-1)

$$\text{Supplementary Equation S20: } forageIntake = \frac{(IC - Qc \times Sg)}{avFVfor}$$

Qc quantity of concentrate

Growth:

$$\text{Supplementary Equation S21: } dailyGrowth = \left( \frac{\frac{UFL_{intake} - GestReq}{BW^{0.75}} - 0.045}{0.0336} \right)^{\frac{1}{1.457}}$$

With UFL intake the ufl intake

With GestReq the UFL requirement for gestation (Supplementary Equation S3).

*Supplementary Table S5: Comparison of the impact of the increase of 1kg of concentrates per cow per day in the model to the actual impact shown in published studies on the daily milk production of a dairy cow*

Time of the lactation	Model output (kg of milk/day/cow)	Literature output (kg of milk/day/cow)
Early lactation (lactation weeks 1-16)	0.75-1.38	0.54-0.88 (McEvoy <i>et al.</i> , 2008)
		0.51-1.18 (Gill and Kaushal, 2000)
		0.92-1.08 (Roche <i>et al.</i> , 2007)
		0.5-1.3 (Kennedy <i>et al.</i> , 2003)
		0.95-1.35 (Kennedy <i>et al.</i> , 2007)
0.50-1.63 (Delaby <i>et al.</i> , 2003)		
Mid lactation (lactation weeks 17-25)	0.5-1.45	0.7-1.1 (Robaina <i>et al.</i> , 1998)
Late lactation (lactation weeks 26-39)	0.2-0.65	0.5-1 (Kennedy <i>et al.</i> , 2003)
		0.42-1.39 (Delaby <i>et al.</i> , 2001)
Whole lactation (lactation weeks 1-39)	0.5-1.12	0.63-1.63 (Fulkerson <i>et al.</i> , 2008)
		0.76-1.1 (Bargo <i>et al.</i> , 2002)
		0.39-0.75 (Reis and Combs, 2000)
		0.33-0.9 (McCarthy <i>et al.</i> , 2007)
		0.23-1.06 (Roche <i>et al.</i> , 2006)
		1.18-0.5 (Horan <i>et al.</i> , 2005)
0.76-1.09 (Tozer <i>et al.</i> , 2004)		
0.60-1.57 (Delaby <i>et al.</i> , 2003)		



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