RESEARCH ARTICLE

External validation of the GrazeIn model of pasture dry matter intake and milk yield prediction for cows managed at different calving dates and stocking rates

Ana I. Roca-Fernández[1,2] and Antonio González-Rodríguez[2]

[1]Universidad de Santiago de Compostela, Escuela Politécnica Superior, Dept. de Producción Vegetal y Proyectos de Ingeniería. Campus Universitario. 27002 Lugo, Spain [2]Instituto Gallego de Calidad Alimentaria, Centro de Investigaciones Agrarias de Mabegondo, Dept. de Producción Animal. Apdo. 10. 15080 La Coruña. Spain

Abstract

The aim was to evaluate the prediction accuracy of pasture dry matter intake (PDMI) and milk yield (MY) predicted by the GrazeIn model using a database representing 124 PDMI measurements at paddock level and 2232 MY measurements at cow level. External validation of the model was conducted using data collected from a trial carried out with Holstein-Friesian cows (n=72) while grazed 28 paddocks and were managed in a 2×2 factorial design by considering two calving dates (CD), with different number of days in milk (DIM), early (E, 29 DIM) *vs.* middle (M, 167 DIM), and two stocking rates (SR), medium (M, 3.9 cows ha⁻¹) *vs.* high (H, 4.8 cows ha⁻¹), under a rotational grazing system. Cows were randomly assigned to four grazing scenarios (EM, EH, MM and MH). The mean observed PDMI of the total database was 14.2 kg DM cow⁻¹ day⁻¹ while GrazeIn predicted a mean PDMI for the database of 13.8 kg DM cow⁻¹ day⁻¹. The mean bias was −0.4 kg DM cow⁻¹ day⁻¹. GrazeIn predicted PDMI for the total database with a relative prediction error (RPE) of 10.0% at paddock level. The mean observed MY of the database was 23.2 kg cow⁻¹ day⁻¹ while GrazeIn predicted a MY for the database of 23.1 kg cow⁻¹ day⁻¹. The mean bias was –0.1 kg cow⁻¹ day⁻¹. GrazeIn predicted MY for the total database with a mean RPE of 17.3% at cow level. For the scenarios investigated, GrazeIn predicted PDMI and MY with a low level of error which made it a suitable tool for decision support systems.

Additional keywords: grass intake; milk production; modeling; decision support system; lactation stage; grazing pressure; dairy cows.

Abbreviations used: ADF (acid detergent fibre); BCS (body condition score); BW (body weight); CD (calving date); CP (crude protein); DHA (daily herbage allowance); DIM (days in milk); DM (dry matter); FV (fill value); GVA (gross value added); HM (herbage mass); IVOMD (*in vitro* organic matter digestibility); MPE (mean prediction error); MSPE (mean square prediction error); MY (milk yield); NDF (neutral detergent fibre); PDIE (protein truly digestible in the intestine); PDMI (pasture dry matter intake); PMY$_{peak}$ (potential milk yield peak); RPE (relative prediction error); SR (stocking rate); UFL (*Unité Fourragère Lait, i.e.*, feed unit for milk production).

Authors' contributions: Both authors conceived, designed and performed the experiment, analysed the data and wrote the paper.

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Correspondence should be addressed to Ana I. Roca-Fernández: anai.roca@usc.es

Introduction

Galician (NW Spain) economy is highly oriented to the primary sector. Approximately, 61% of the gross value added (GVA) in the region comes from animal production. Milk is the most important economic driver of the area, accounting for 30% of GVA, and it represents more than 35% of the total Spanish milk quota (2.2 over 6.0 million of tons). However, only 8% of Galician permanent pastures are utilized for milk production and just 16% are associated to sown pastures, forage maize and crops (MARM, 2010).

Pasture-based milk production systems have been decreasing considerably over the last 30 years in other European regions (Bourgeois, 2002) as Galicia, where climatic conditions are adequate for pasture growth (Mayne & Peyraud, 1996) all year around, and the number of cows which are kept indoors for all or part of

the grazing season has increased considerably (Van den Pol-van Dasselaar *et al.*, 2008). Nevertheless, due to an increased world demand for dairy products and high volatility in the price of feedstuffs for animal nutrition is nowadays envisaged that a larger proportion of the milk produced in humid areas might come, after the abolition of EU milk quotas in 2015, from grazing dairy systems as pasture is the cheapest source of nutrients available for feeding ruminants (Dillon, 2006).

Productivity within such grazing dairy systems depends on achieving a balance between the competing objectives of high pasture dry matter intake (PDMI) and milk yield (MY) per animal by maximizing pasture production per hectare, sward quality and pasture utilization (McCarthy *et al.*, 2014; 2016). This increase in milk production may be achieved by an increase in stocking rate (SR) in conjunction with the optimization of mean calving date (CD) at farm level (Dillon *et al.*, 2008). The SR (cows ha^{-1}), defined as the number of animals per unit area of land used during a specified period of time (Allen *et al.*, 2011), is acknowledged as the main driver of productivity (McCarthy *et al.*, 2014). A recent review of several SR experiments, for which there was no additional supplement fed at the highest SR, reported a 0.20 increase in milk production per ha arising from a one cow per ha increase in SR (McCarthy *et al.*, 2011). In addition to SR, CD is an important determinant of feed utilization through its impact on the alignment between cow requirements and pasture supply (McCarthy *et al.*, 2013), and altering the mean CD may have a relevant role in reducing the reliance of dairy farms on purchased feeds, particularly at high SR in early lactation (McCarthy *et al.*, 2016). However, few studies (McCarthy *et al.*, 2012a,b; 2014) have attempted to quantify the effect of mean CD in spring on PDMI and MY or elucidate any potential interactions with SR.

Decision support tools developed to help dairy farmers gain confidence in grazing management need to be able to predict PDMI and MY of grazing dairy cows with easy-to-obtain variables at the farm level (Delagarde *et al.*, 2011a). The number of models predicting PDMI at grazing is small in comparison with those predicting DM intake for indoor systems (Caird & Holmes, 1986; Vázquez & Smith, 2000; Delagarde & O'Donovan, 2005). Moreover, the number of models available for predicting both PDMI and MY is even smaller (Baudracco *et al.*, 2010; Delagarde *et al.*, 2011a). Delagarde & O'Donovan (2005) investigated the prediction performance of five published PDMI prediction models. Results from their investigation show that the model with the lowest error of prediction had a large number of easily obtainable animal, sward, grazing management and supplementation variables

and also had PDMI and MY as outputs (Delagarde *et al.*, 2011a; Faverdin *et al.*, 2011). This model, called GrazeIn, was designed to predict PDMI and MY of grazing dairy cows (Faverdin *et al.*, 2011; Delagarde *et al.*, 2011a). Its first external validation was carried out by Delagarde *et al.* (2011b) using a dataset of 206 grazing herds from 20 trials conducted at five European research institutions to evaluate the effect of supplementation at pasture (mainly with concentrate) on PDMI and MY predictions. O'Neill *et al.* (2012a,b and 2013) also decided to evaluate this model using a database of 522 grazing herds from 19 trials conducted with dairy cows in Ireland to assess the accuracy of the GrazeIn model for PDMI and MY predictions taking into account three grazing seasons (spring, summer and autumn) and three dairy cow's lactation stages (early, middle and late lactation).

The aim of the current study was to make for the first time an external validation of the GrazeIn model under Galician conditions (NW Spain) by focusing the attention on two of the main factors (CD and SR) affecting pasture productivity, intake and sward quality in pasture-based milk production systems. For that, the prediction accuracy of the model for estimation of PDMI and MY of dairy cows fed at pasture is evaluated using four different grazing scenarios by combining two CD and two SR.

Material and methods

Model description

The GrazeIn model is a prediction model that simulates PDMI and MY of grazing dairy cows. It was developed by Faverdin *et al.* (2011) and Delagarde *et al.* (2011a) as part of the EU-funded Grazemore decision support system project (Mayne *et al.*, 2004). Prediction accuracy of GrazeIn was initially evaluated by an external validation of the model from an independent dataset obtained from five EU research centers in which 1292 dairy cows were involved (Delagarde *et al.*, 2011b). O'Neill *et al.* (2012a,b) also conducted an evaluation of the model, using a database in which 1526 dairy cows were involved and 8787 per cow intake records were obtained, to assess the accuracy of GrazeIn predictions for PDMI and MY in the Irish context. In all cases (Delagarde *et al.*, 2011b; O'Neill *et al.*, 2012a,b), the predictions of GrazeIn were compared to the observed PDMI and MY values measured experimentally as it was done in the current study where 28 paddocks and 72 dairy cows were involved.

In all cases, for running the model and to calculate the predicted PDMI and MY the following variables

were recorded. For animals, potential peak milk yield (PMY_{peak}), stage of lactation, body weight (BW), body condition score (BCS), parity, week of lactation, age, milk fat content, milk protein content, week of conception and calf birth weight during the lactation were considered. For pastures, main species, crude protein (CP) content, *in vitro* organic matter digestibility (IVOMD), herbage mass (HM), daily herbage allowance (DHA) and pasture height were included. For supplements, amount eaten and nutritive value were introduced. For grazing management, daily offered area, residency time in each paddock and daily time at pasture were inserted. The sward characteristic input variables: fill value (FV), *unité fourragère lait* (UFL) and protein truly digestible in the intestine (PDIE) were calculated according to INRA (2007) from the chemical composition of the pasture samples mainly DM, CP and IVOMD. The IVOMD was determined using the *in vitro* neutral detergent cellulose method as mentioned by Morgan *et al.* (1989). The FV of concentrates was calculated in the model by iterative procedure considering substitution rate and energy balance as described by Faverdin *et al.* (2011). This means that PDMI cannot be estimated from known concentrate DM intake, but after substitution rate prediction. Interactions between grazing management, supplements and herd characteristics are estimated in the GrazeIn model by an iterative process, whereby values are arrived at by convergence [following the assumptions of Faverdin *et al.* (2011) and Delagarde *et al.* (2011a,b)].

External validation of the GrazeIn model

Description of the CIAM database

The external validation of the GrazeIn model was carried out using data collected from a grazing experiment conducted at the *Centro de Investigaciones Agrarias de Mabegondo* (CIAM), situated in Galicia, Spain (43°15'N; 81°18'W), from spring to summer in 2007, on 5-yr old pastures (initially sown with a mixture of 22 kg ha^{-1} of *Lolium perenne* cv. Brigantia and 4 kg ha^{-1} of *Trifolium repens* cv. Huia). The database was created by testing four grazing scenarios in which two main factors were studied: two different calving dates (CD), considering two groups of cows with different number of days in milk (DIM), early (E, 29 DIM) *vs.* middle (M, 167 DIM), and two different stocking rates (SR), considering animals managed at medium (M, 3.9 cows ha^{-1}) *vs.* high (H, 4.8 cows ha^{-1}), with 4 and 5 grazing rotations conducted during 125 and 138 days for the medium and high SR treatments, respectively. A randomized block design with a 2×2 factorial arrangement of treatments (EM, EH, MM

and MH) was applied to determine the effect of CD and SR. The grazing treatments were imposed in four separately farmlets: EM (E, early calving date and M, medium stocking rate), EH (E, early calving date and H, high stocking rate), MM (M, middle calving date and M, medium stocking rate) and MH (M, middle calving date and H, high stocking rate). In total, 72 multiparous (lactation number, 3.4 ± 1.52) Holstein-Friesian cows were involved. Animals from each farmlet (EM, n=22; EH, n=22; MM, n=14; MH, n=14) were rotationally grazing four independent areas of pasture by assigning them to a surface of 4.1, 5.3, 3.4, and 3.9 ha, respectively. The total area for grazing was 17.4 ha divided in 28 paddocks of approximately 0.62 ha each. Pastures showed high proportion of perennial ryegrass (more than 70%), low proportion (less than 10%) of white clover and other species (less than 20%).

Observed pasture dry matter intake and milk yield measurements

Observed PDMI was estimated at paddock level using a sward cutting technique. Five random samples (0.33 m × 0.33 m) were taken per paddock in different areas before and after the cows were grazing that specific paddock at each rotation, cutting to 4 cm above ground level with battery-operated shears, to determine HM per hectare. Each sample was then dried at 70°C for 24 h and 0.5 kg was milled, vacuum packed and stored at −20°C until later chemical analysis at the CIAM's laboratory. Pasture chemical composition was determined using infrared reflectance spectroscopy by NIRS System 6500 (Foss Analytical, Hillerød, Denmark), applying the Castro-García's (1994) equations of calibration for determination of CP, acid detergent fibre (ADF), neutral detergent fibre (NDF), water soluble carbohydrates (WSC) and IVOMD. Five pre- and post-grazing sward heights were taken using a rising plate meter (Frame, 1981) before and after cutting pasture in each paddock at each rotation. Estimates of HM before and after grazing were used to calculate (Freer, 1960; Campbell, 1966; Hodgson, 1979):

–Herbage mass (HM) as kg DM ha^{-1}: $(A_i) + n_i*[(A_i-D_{i-1})*r_i^{-1}]$

–Daily herbage allowance (DHA) as kg DM cow^{-1} day^{-1}: $HM*(cow*day)^{-1}$

–Pasture dry matter intake (PDMI) as kg DM cow^{-1} day^{-1}: $[(A_i-D_i) + n_i*[(A_i-D_{i-1}*r_i^{-1})]]*(cow*day)^{-1}$

–Herbage utilization as %: $(PDMI*DHA^{-1})*100$,

where A_i is the kg of DM per ha produced by a paddock before being grazed; D_i is the kg of DM ha^{-1} remained in a paddock after being grazed; D_{i-1} is the kg of DM ha^{-1} remained in a paddock after previous grazing happened in that paddock and before it was

grazed again; n_i is the number of grazing days per paddock (standing time) and r_i is the number of days per paddock between D_{i-1} and A_i.

The second term in HM and PDMI estimations $n_i*[(A_i-D_{i-1})\ r_i^{-1}]$ is a pasture growth correction factor. No direct measure was made of pasture growth during grazing but the pasture growth during the previous days' rest period was known and the mean estimate for each paddock for each rotation was applied as a correction factor. It was assumed that the difference between the mean pasture growth rate of a sward during the rest period and the mean pasture growth rate during the grazing (less than 2.5 days) would not be large enough to invalidate the estimate of HM, DHA and PDMI (Freer, 1960).

All cows were supplemented at pasture from calving to the second grazing rotation with silage (60% grass and 40% corn) and concentrate. The silage and concentrate DM intakes were daily determined from the difference between the amount offered and the residue on each day, summing these values during the experimental period for each treatment. The DM losses were estimated following assumptions from other studies, considering 20% for grass silage (González *et al.*, 1989) and 12% for corn silage (Phipps & Wilkinson, 1985). The level of concentrate given to the animals was progressively reduced as grazing season progressed and cows' lactation stage advanced. At the beginning of the experiment, cows at the early and middle CD received 6 and 4 kg DM cow^{-1} day^{-1} of concentrate, respectively. At the end of April, concentrate supplementation level was reduced to 2 and nil kg DM cow^{-1} day^{-1} for dairy cows at the early and middle CD, respectively. The concentrate contained a mixture of the following six ingredients: barley (81%), soya flour (14%), vitamin mineral corrector (0.2%), dicalcium phosphate (2%), calcium carbonate (2%) and sodium chloride (0.8%).

Daily MY from each cow was recorded by Alprow System (Alfa DeLaval, France) and samples were weekly collected, from two successive evening (Tuesday) and morning (Wednesday) milkings. Samples were preserved with potassium dichromate and stored at −20°C for milk composition analysis. Milk protein and fat were determined in the *Laboratorio Interprofesional Gallego de Análisis de Leche* (LIGAL) using infrared spectroscopy by MilkoScan FT6000 (Foss Electric, Hillerød, Denmark).

Weekly individual BW from each cow was registered and BCS was scored twice a month, by one experienced observer on a 1 to 5 scale (1= severe undercondition and 5 = severe overcondition) with 0.25 increments as described Wildman *et al.* (1982), during all the experiment.

Evaluating the GrazeIn model using the CIAM database: Grazing scenarios investigated

The evaluation investigated the accuracy with which GrazeIn predicted PDMI at paddock level and MY at cow level compared with observed PDMI and MY from the CIAM database. The database contains per cow per day estimates of 124 PDMI measurements registered at paddock level (from a total of 28 paddocks) and 2232 MY measurements recorded at cow level (from a total of 72 multiparous Holstein-Friesian cows). The animal measurements were collected from four herds of cows assigned to four different grazing scenarios, by considering four treatments (EM, EH, MM and MH), which were focused on the evaluation of two main factors: differences on calving date (E, early *vs*. M, middle) and stocking rate (M, medium *vs*. H, high). The 124 PDMI measurements at paddock level were obtained as the sum of the number of paddocks grazed × number of rotations per herd (EM = 8 × 4 = 32; EH = 6 × 5 = 30; MM = 8 × 4 = 32; MH = 6 × 5 =30). The 2232 MY measurements at cow level were obtained as the sum of the number of cows × number of paddocks grazed × number of rotations per herd (EM = 22 × 8 × 4 = 704; EH = 22 × 6 × 5 = 660; MM = 14 × 8 × 4 = 448; MH = 14 × 6 × 5 = 420). A detailed description of the database illustrating the mean, standard deviation, minimum and maximum values for each grazing scenario evaluated with some of the key variables which were introduced as input variables in the GrazeIn model for its external validation can be found in Tables 1 and 2.

Statistical analysis

The PDMI and MY were predicted by GrazeIn using data recorded on the grazing experiment described previously, taking into account 124 PDMI and 2232 MY measurements, as input data. The database was subdivided into two categories: by calving date (E, early *vs*. M, middle) and by stocking rate (M, medium *vs*. H, high), and then the accuracy of GrazeIn was also investigated taking into account results obtained for each grazing scenario analyzed separately. The observed (O) and predicted (P) values for PDMI at paddock level and MY at cow level were compared using linear regression of the observed upon the predicted values. The accuracy of GrazeIn was determined using the origin, slope and R^2 of the relationships between observed and predicted values as proposed by Hayirli *et al.* (2003). The correlation between observed and predicted values indicates closeness of both values. The accuracy of GrazeIn was

evaluated using the most common deviance measures as recommended by Rook *et al.* (1990), namely mean prediction error (MPE), relative prediction error (RPE) and the mean square prediction error (MSPE) (Hayirli *et al.*, 2003).

The MPE is the square root of the MSPE and indicates the average precision of the prediction (Rook *et al.*, 1990). The RPE is the expression of MPE as a percentage of the observed PDMI/MY. It is calculated by dividing the MPE by the mean observed value O_m and multiplying the result obtained previously by 100. The RPE is expressed in %. The lower the RPE the more accurate is the prediction.

The MSPE is defined as the sum of three components, namely the mean bias, line bias and random variation (Bibby & Toutenburg, 1977). These are represented in the following equation:

$$\text{MSPE} = 1/n \sum (O - P)^2 = (O_m - P_m)^2 + S_P{}^2 (1 - b)^2 + S_O{}^2 (1 - r^2)$$

where n is the number of predicted (*P*) and observed (*O*) pairs of grazing herds compared; O_m and P_m are the means of the observed and predicted PDMI/MY, respectively; $S_O{}^2$ and $S_P{}^2$ are the variances of the observed and predicted PDMI/MY, respectively; *b* is the slope of the regression of observed upon predicted, and *r* is the correlation coefficient of observed and predicted.

In the evaluation of GrazeIn, the mean bias represents the robustness of the model (Roseler *et al.*, 1997). A large mean bias ($O_m - P_m$) indicates that predicted values are higher or lower than the observed values. The line bias [$S_P{}^2 (1 - b)^2$] is the slope of the regression of observed upon predicted. If the slope is higher than 1.0, the model tends to over-predict at low observed values and under-predict at high observed values. A large line bias is mainly indicative of inadequacies in the structure of the model (Roseler *et al.*, 1997). The random variation component [$S_O{}^2 (1 - r^2)$] of the MSPE is a function of the coefficient of variation of the regression of observed upon predicted PDMI/MY (r^2) and the variance ($S_O{}^2$) of the observed data (Fuentes-Pila *et al.*, 1996). The proportion of the MSPE attributed to random variation should be high for a good level of accuracy. This random variation may be due to animal variation and experimental variation in the measured data. If the proportion of random variation is low, then the most part of the error in the MSPE is attributed to the mean and line bias. For the analysis, the results are presented in terms of the proportional contribution of each of the three components to the MSPE (Rook *et al.*, 1990) to highlight areas where GrazeIn is introducing error into the predicted values as reported by Delagarde *et al.* (2011a) and O´Neill *et al.* (2012a,b).

Results

There was a large range in the cow and pasture characteristics, and grazing management input variables in the CIAM database used to perform the external validation of the GrazeIn model (Table 1). The large range in the inputs variables tested the robustness of GrazeIn. The grazing herds ranged in PMY_{peak} (33.7-37.9 kg cow^{-1} day^{-1}), week of lactation (13-29), milk protein content (28.7-31.7 g kg^{-1}), milk fat content (35.6-38.9 g kg^{-1}), age (51-63 months), BW (564-597 kg), BCS (2.8-3.0) and BCS at calving (3.4-3.6). However, no differences were found on week of conception (13.5) and calf weight (44.5 kg) among herds. The pastures grazed by the four herds ranged in pre-grazing (14.4-17.0 cm) and post-grazing pasture heights (5.6-6.7 cm), pre-grazing (1877-2928 kg DM ha^{-1}) and post-grazing HM (672-792 kg DM ha^{-1}), and in DHA (22.7-32.4 kg DM cow^{-1} day^{-1}). On average, E herds were fed with a total of +1.4 kg DM cow^{-1} day^{-1} compared to M herds (16.8 kg DM cow^{-1} day^{-1}) mainly attributed to higher supplementation in E than in M herds (Table 2). FV, UFL and PDIE values for pastures and supplements were inside the ranges established by INRA (2007). No differences were found among herds for any of these values as animals were fed with the same type of supplement but in different amounts according to the grazing group where were assigned. The pasture offered ranged in DM (184-200 g kg^{-1}), CP (127-156 g kg^{-1} DM), ADF (287-310 g kg^{-1} DM), NDF (515-537 g kg^{-1} DM), WSC (154-165 g kg^{-1} DM) and IVOMD (71.7-77.6%). The MY ranged from 18.5 to 26.6 kg cow^{-1} day^{-1} among herds and total DM intake ranged from 16.7 to 18.4 kg cow^{-1} day^{-1} of feed ingested, respectively. However, PDMI was similar among the four herds (average of 14.2 kg DM cow^{-1} day^{-1}).

Pasture dry matter intake prediction

Total database

GrazeIn predicted a mean PDMI of 13.8 kg DM cow^{-1} day^{-1} at herd by paddock level (Table 3). Over the 124 PDMI measurements carried out, the model predicted PDMI with a mean RPE of 10.0% and a mean bias of –0.44 kg DM cow^{-1} day^{-1}. The MSPE in terms of its components came from random variation (0.98), with a small proportion coming from the line (0.00) and the mean bias (0.02).

By calving date

The mean observed PDMI was higher (+0.7 kg DM cow^{-1} day^{-1}) than the predicted PDMI for early CD herds (13.6 kg DM cow^{-1} day^{-1}), without differences between observed and predicted PDMI among middle CD herds (14.1 kg DM cow^{-1} day^{-1}). The RPE ranged

Table 1. Mean and range of the cow, pasture and grazing management variables which were used for the external validation of GrazeIn at herd level (EM, EH, MM and MH)[1] by using observed pasture measurements (n=124) and animal data (n=72) recorded from the CIAM database.

	Mean				Standard deviation				Minimum				Maximum			
	EM	EH	MM	MH	EM	EH	MM	MH	EM	EH	MM	MH	EM	EH	MM	MH
(a) Cow characteristics																
Potential peak milk yield (kg cow^{-1} day^{-1})	37.9	37.2	35.1	33.7	7.80	6.90	6.68	6.08	25.6	25.0	22.9	21.9	51.9	49.5	46.8	45.9
Week of lactation	15	13	28	29	6.1	6.0	5.8	6.5	1	1	14	13	27	27	43	43
Milk protein content (g kg^{-1})	29.2	28.7	31.7	30.7	2.10	1.96	2.50	1.90	23.5	23.5	25.2	25.2	39.2	35.2	38.8	37.2
Milk fat content (g kg^{-1})	36.3	35.6	38.9	36.8	5.11	5.04	5.14	4.86	23.9	23.4	25.1	24.2	54.1	52.2	53.6	49.6
Week of conception	13	13	14	14	3.3	3.6	4.1	4.9	7	6	8	4	20	20	22	24
Calf weight (kg)	45	44	45	44	4.6	4.2	6.4	4.9	38	35	35	33	55	53	57	55
Age (months)	51	56	63	61	24.2	25.8	30.0	31.1	27	27	34	32	127	126	113	150
Body weight (kg)	573	564	597	574	85.1	69.8	70.6	56.8	447	425	480	462	783	730	740	739
Body condition score (0-5)	2.8	2.8	3.0	2.9	0.60	0.51	0.53	0.45	2.3	2.3	2.3	2.3	4.5	4.3	4.3	4.3
Body condition score at calving (0-5)	3.4	3.4	3.6	3.4	0.79	0.79	0.69	0.64	2.5	2.5	2.5	2.5	5.0	5.0	4.8	4.5
(b) Pasture characteristics, intake & grazing management																
Pasture intake (kg DM^2 cow^{-1} day^{-1})	14.4	14.3	14.1	14.1	3.09	3.26	3.27	3.30	2.2	4.4	4.9	5.0	19.5	19.6	18.5	19.4
Pasture Fill value (FU^3 kg^{-1} DM)	1.05	1.04	1.04	1.03	0.043	0.041	0.044	0.038	0.98	0.97	0.96	0.93	1.18	1.14	1.13	1.10
Pasture UFL^4 (UFL kg^{-1} DM)	0.84	0.88	0.87	0.88	0.089	0.093	0.079	0.092	0.66	0.69	0.69	0.71	0.99	1.02	1.01	1.03
Pasture PDIE^5 (g kg^{-1} DM)	82	86	86	88	8.4	8.7	7.5	8.1	57	67	65	71	95	100	102	102
Pre-grazing pasture height (cm)	17.0	14.8	16.6	14.4	7.05	4.08	6.63	5.49	5.4	5.2	6.4	5.6	32.8	23.6	34.2	29.2
Post-grazing pasture height (cm)	6.1	5.6	6.7	5.8	1.93	1.79	2.42	2.15	4.0	4.0	4.0	4.0	10.7	10.2	13.5	12.3
Pre-grazing herbage mass (kg DM ha^{-1})	2180	2095	2928	1877	1165.5	1011.2	1775.5	865.8	428	344	612	267	4853	4395	6747	3514
Post-grazing herbage mass (kg DM ha^{-1})	741	672	792	718	182.3	147.1	322.6	231.8	461	350	380	325	1047	1012	1639	1147
Daily herbage allowance (kg DM cow^{-1} day^{-1})	24.6	22.7	32.4	26.8	11.49	9.00	11.73	11.30	6.7	4.5	13.5	10.6	75.2	54.1	69.2	66.4

[1]EM (E, early calving date and M, medium stocking rate), EH (E, early calving date and H, high stocking rate), MM (M, middle calving date and M, medium stocking rate) and MH (M, middle calving date and H, high stocking rate). [2]DM: dry matter. [3]FU: forage unit. [4]UFL: *Unité Fourragère Lait* (feed unit for milk production, 1 UFL = 7.115 MJ of net energy). [5]PDIE: Protein truly digestible in the intestine, with energy-limiting microbial synthesis in the rumen (INRA, 2007).

from 6.4 to 12.3% for MM and EM herds, respectively. The bias between predicted and observed values ranged from –0.75 to +0.32 kg DM cow^{-1} day^{-1} for EH and MM herds, respectively. The proportion of the MSPE attributed to random variation was higher in middle than in early CD herds (0.99 *vs*. 0.86, respectively).

By stocking rate

The mean observed PDMI was higher than the predicted for medium SR herds (+0.20 kg DM cow^{-1} day^{-1}). GrazeIn predicted lower PDMI (–0.55 kg DM cow^{-1} day^{-1}) than observed for high SR herds. The RPE ranged on average from 9.0 to 9.3% for H and M herds. The proportion of the MSPE attributed to random variation was higher in high than in medium SR herds (0.94 *vs*. 0.90, respectively).

Figure 1 (a and b) shows the relationship between predicted and observed PDMI at herd by paddock level in medium and high SR herds when different CD are considered. From that, it is deduced that GrazeIn

Table 2. Mean and range of pasture and supplements quality, milk yield and intake variables which were used for the external validation of GrazeIn at herd level (EM, EH, MM and MH)[1] by using observed nutritive value (n=124) and cow measurements (n=2232) from the CIAM database.

	Mean				Standard deviation				Minimum				Maximum			
	EM	EH	MM	MH	EM	EH	MM	MH	EM	EH	MM	MH	EM	EH	MM	MH
a) Pasture chemical composition																
Dry matter (g kg⁻¹)	200	186	191	184	37.3	35.6	42.4	35.7	160	137	141	131	300	275	351	254
Crude protein (g kg⁻¹ DM)	127	141	141	156	30.4	33.4	30.0	35.2	47	71	63	96	180	201	214	220
Acid detergent fibre (g kg⁻¹ DM)	310	288	292	287	56.2	54.9	52.6	46.2	216	201	216	206	422	416	401	393
Neutral detergent fibre (g kg⁻¹ DM)	537	515	527	515	82.0	81.6	69.9	66.0	400	377	406	405	712	698	684	679
Water soluble carbohydrates (g kg⁻¹ DM)	156	165	154	161	59.1	62.0	51.8	57.3	35	55	11	57	262	282	262	271
In vitro organic matter digestibility (%)	71.7	73.9	73.7	77.6	4.33	4.96	4.12	6.30	61.3	63.8	63.1	64.1	80.3	81.3	81.1	89.8
b) Supplementation conditions																
Grass silage intake (kg DM cow⁻¹ day⁻¹)	0.5	0.4	0.8	0.7	0.89	0.83	1.24	1.22	n.s.[4]	n.s.	n.s.	n.s.	2.6	2.4	3.6	3.6
Grass silage Fill value (FU kg⁻¹ DM)	1.25	1.25	1.25	1.25	0	0	0	0	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Grass silage UFL[2] (UFL kg⁻¹ DM)	0.74	0.74	0.74	0.74	0	0	0	0	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Grass silage PDIE[3] (g kg⁻¹ DM)	49	49	49	49	0	0	0	0	49	49	49	49	49	49	49	49
Corn silage intake (kg DM cow⁻¹ day⁻¹)	0.6	0.5	0.9	0.9	1.01	0.97	1.42	1.39	n.s.	n.s.	n.s.	n.s.	3.0	2.9	4.1	4.1
Corn silage Fill value (FU kg⁻¹ DM)	0.97	0.97	0.97	0.97	0.015	0.015	0.015	0.015	0.95	0.95	0.95	0.95	0.98	0.98	0.98	0.98
Corn silage UFL (UFL kg⁻¹ DM)	0.89	0.89	0.89	0.89	0.007	0.007	0.007	0.007	0.88	0.88	0.88	0.88	0.89	0.89	0.89	0.89
Corn silage PDIE (g kg⁻¹ DM)	63	63	64	64	1.5	1.5	1.5	1.5	62	62	62	62	65	65	65	65
Concentrate intake (kg DM cow⁻¹ day⁻¹)	2.9	2.7	1.0	1.0	1.31	1.28	1.42	1.42	1.8	1.8	n.s.	n.s.	5.3	5.3	3.5	3.5
Concentrate UFL (UFL kg⁻¹ DM)	1.09	1.09	1.09	1.09	0	0	0	0	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
Concentrate PDIE (g kg⁻¹ DM)	131	131	131	131	0	0	0	0	131	131	131	131	131	131	131	131
c) Observed milk yield & total DM intake																
Milk yield (kg cow⁻¹ day⁻¹)	26.6	24.0	20.7	18.5	8.16	7.61	6.25	5.77	9.5	7.6	8.2	5.0	49.7	47.0	37.0	36.9
Total intake (kg DM cow⁻¹ day⁻¹)	18.4	17.9	16.8	16.7	2.61	2.18	2.03	1.77	12.9	10.0	13.4	11.8	24.0	23.7	22.1	21.6

[1,2,3] See Table 1. [4]n.s.: no supplement was eaten by animals.

predicts variations on PDMI in a realistic manner over a range of scenarios.

Milk yield prediction

Total database

The mean observed MY for the four herds of cows from the CIAM database was 23.2 kg cow⁻¹ day⁻¹ (Table 3).

GrazeIn predicted a mean MY of 23.1 kg cow⁻¹ day⁻¹ at herd by cow level. Over the 2232 MY measurements carried out at cow level, the model predicted MY with a mean RPE of 17.3% and a mean bias of –0.06 kg cow⁻¹ day⁻¹. The MSPE in terms of its components came from random variation (0.98), with a small proportion coming from the line bias (0.01) and the mean bias (0.01).

Table 3. Prediction accuracy of the GrazeIn model for pasture dry matter intake (kg DM cow⁻¹ day⁻¹) estimation at herd by paddock level and milk yield (kg cow⁻¹ day⁻¹) estimation at herd by cow level using observed pasture measurements (PDMI, n=124) and milk yield measurements (MY, n=2232) recorded from the CIAM database for the external validation of the model under four grazing scenarios (EM, EH, MM and MH).

Category	Data	Observed (O)	Predicted (P)	Regression of O upon P			Bias (P-O)	MSPE[1]	Proportion of MSPE			MPE[2]	RPE[3] (%)
				Origin	Slope	R			Mean Bias	Line Bias	Random variation		
a) Pasture dry matter intake (kg DM cow⁻¹ day⁻¹)													
Total PDMI measurements	124[5]	14.2	13.8	-1.01	1.11	0.80	-0.44	2.02	0.02	0.00	0.98	1.42	10.0
EM[4]	32	14.4	13.7	-2.43	1.23	0.67	-0.73	3.14	0.17	0.02	0.82	1.77	12.3
EH	30	14.3	13.5	0.10	1.05	0.80	-0.75	1.90	0.11	0.00	0.89	1.38	9.7
MM	32	14.1	14.4	-1.03	1.05	0.92	0.32	0.81	0.01	0.00	0.99	0.90	6.4
MH	30	14.1	13.8	-0.58	1.06	0.87	-0.26	1.38	0.01	0.00	0.99	1.18	8.4
a) Milk yield (kg cow⁻¹ day⁻¹)													
Total MY measurements	2232[6]	23.2	23.1	-0.70	1.03	0.68	-0.06	16.13	0.01	0.01	0.98	4.02	17.3
EM	704	26.6	26.2	-2.29	1.10	0.75	-0.38	12.93	0.19	0.05	0.76	3.60	13.5
EH	660	24.0	24.3	0.72	0.96	0.64	0.31	24.04	0.24	0.02	0.74	4.90	20.4
MM	448	20.7	20.4	-1.90	1.11	0.69	-0.29	10.27	0.09	0.02	0.89	3.21	15.5
MH	420	18.5	18.5	-1.43	1.08	0.66	-0.02	13.21	0.00	0.02	0.98	3.64	19.6

[1]Mean square prediction error. [2]Mean prediction error. [3]Relative prediction error. [4]See Table 1. [5]Sum of paddocks grazed (n=8 in EM and MM; n=6 in EH and MH) × number of rotations per herd (n=4 in EM and MM; n=5 in EH and MH). [6]Sum of cows (n= 22 in EM and EH; n=14 in MM and MH) × number of paddocks grazed (n=8 in EM and MM; n=6 in EH and MH) × number of rotations per herd (n=4 in EM and MM; n=5 in EH and MH).

By calving date

The mean observed MY was slightly higher to the predicted MY for early CD herds (+0.05 kg cow⁻¹ day⁻¹) and middle CD herds (+0.15 kg cow⁻¹ day⁻¹), respectively. The RPE ranged from 13.5 to 20.4% for EM and EH herds, respectively. The bias between predicted and observed values ranged from –0.38 to 0.31 kg cow⁻¹ day⁻¹ for EM and EH herds, respectively. The proportion of the MSPE attributed to random variation was higher in middle than in early CD herds (0.93 *vs*. 0.75, respectively).

By stocking rate

The mean observed MY was slightly higher to the mean predicted MY for medium SR herds (+0.35 kg cow⁻¹ day⁻¹) while slightly lower for high SR herds (–0.15 kg cow⁻¹ day⁻¹), respectively. The RPE ranged on average from 14.5 to 20.0% for M and H herds. The proportion of the MSPE attributed to random variation was higher in high than in medium SR herds (0.86 *vs*. 0.82, respectively).

Figure 1 (c and d) shows the relationship between predicted and observed MY at herd by cow level in medium and high SR herds when different CD are considered. From that, it is deducted that GrazeIn is able to predict variations on MY in a realistic manner over a range of grazing scenarios.

Discussion

On the total database, the line biases for both PDMI and MY predictions were low, indicating an adequate general structure of the model. GrazeIn seems to predict accurately PDMI at herd by paddock level and MY at herd by cow level over a wide range of the grazing scenarios investigated in the current study (different CD, ranging from early to middle, and SR, ranging from medium to high), as it was previously shown by other simulations reported by Delagarde *et al.* (2011b) and O'Neill *et al.* (2012a,b) in which other grazing scenarios were performed to evaluate the accuracy of the model. The wide range of reported values, 2-20 kg DM cow⁻¹ day⁻¹ for PDMI and 5-50 kg cow⁻¹ day⁻¹ for MY, is in line with those indicated by Delagarde *et al.* (2011b), 7-22 kg DM cow⁻¹ day⁻¹ for PDMI and 10-40 kg cow⁻¹ day⁻¹ for MY, which established that range as a good preliminary condition to validate the main fluctuations of the model and the predicted interactions between animals, swards, supplements and grazing management. Average responses of PDMI (13.8 kg DM cow⁻¹ day⁻¹) and MY (23.1 kg cow⁻¹ day⁻¹) are predicted in a realistic manner and are close to those reported by Delagarde *et al.* (2011b) for PDMI (14.2 kg DM cow⁻¹ day⁻¹) and MY (24.7 cow⁻¹ day⁻¹). It is remarkable
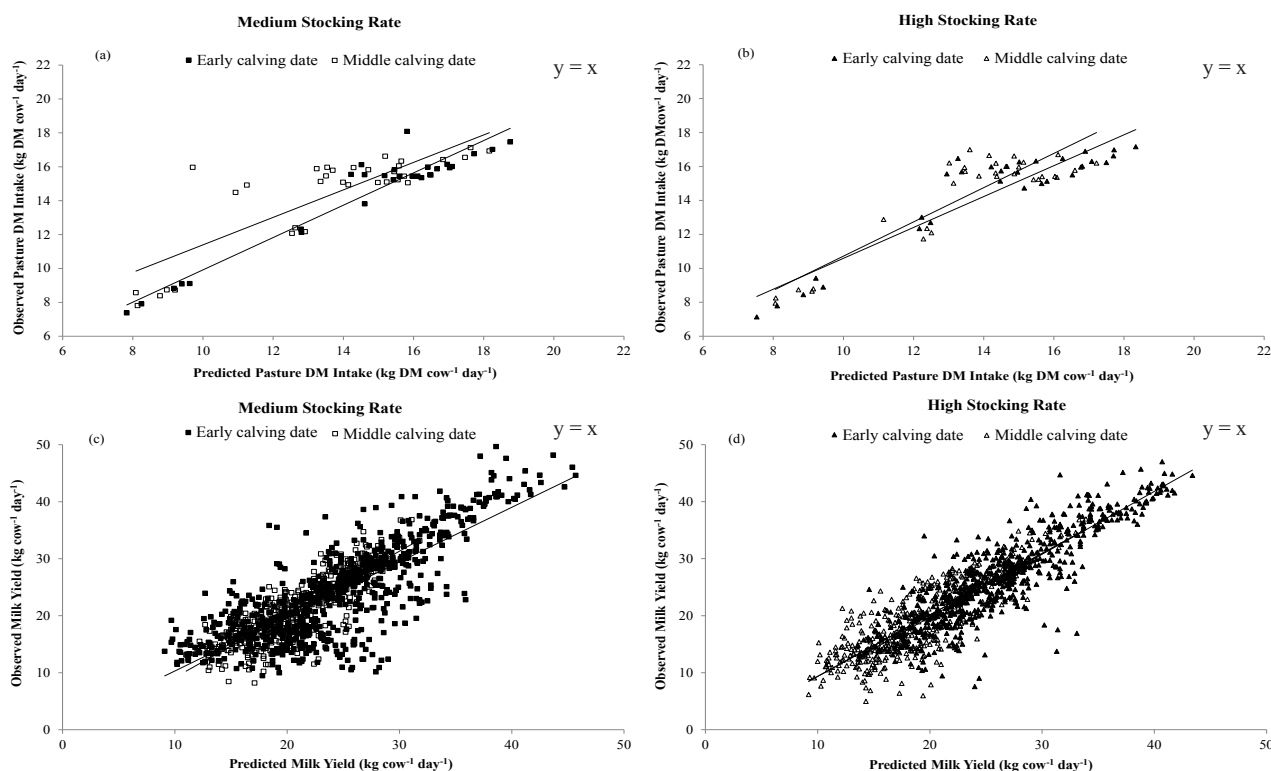
Figure 1. Relationships between predicted and observed pasture dry matter intake (a-b) and milk yield (c-d) using data recorded from four herds of Holstein-Friesian cows managed at two stocking rates (medium *vs*. high) when two calving dates were considered (early *vs*. middle).

from the current study that RPE of MY (17%) at cow level was relatively higher than that of PDMI (10%) at paddock level and it could be explained by the fact that high RPE of PDMI might have had a carry-over effect on high RPE of MY as MY is partly calculated from the model by considering total intake (sum of supplements intake and PDMI). Moreover, attention has to be paid to the interpretation of the results due to MY was estimated at cow level while PDMI at paddock level from the current study.

Pasture dry matter intake prediction

The overall accuracy of GrazeIn for PDMI prediction in the current study (10%) is in line with that reported by Delagarde *et al.* (2011b) and O'Neill *et al.* (2012a) at herd by paddock level (16 and 12%, respectively). Keady *et al.* (2004) evaluating five intake models for dairy cows fed on grass silages also reported RPE values ranging from 10 to 20%. Rook *et al.* (1990), testing several intake models for beef cattle fed on grass silages, reported an average RPE of 15%, ranging from 8 to 26% according to the model. The RPE range in our study fluctuated between 6 to 12% for the grazing scenarios investigated. Although a model precision of 10% would be better for practical use, this threshold

appears difficult to achieve, particularly in the case of grazing (Delagarde *et al.*, 2011b). In fact, testing the performance of a model presupposes implicitly that the observed values used as reference are known with certainty, however, it is difficult to achieve that due to the complexity of PDMI determination. Nonetheless, numerous methodological studies have shown that the mean error of PDMI measurement at grazing is frequently higher than 10%, corresponding to residual standard deviation of PDMI measurement for grazing dairy cows ranging from 1.0 to 2.0 kg cow^{-1} day^{-1} (Peyraud, 1997; Lantinga *et al.*, 2004; Penning, 2004). According to Fuentes-Pila *et al.* (1996), an RPE of <10% may be considered satisfactory for prediction of PDMI, between 10 and 20% as relatively good or acceptable, and >20% as lacking in robustness. As a result, considering these assumptions, the present study showed that the GrazeIn model was relatively good at PDMI prediction (RPE = 10%) for all the grazing scenarios under evaluation. The difference in the RPE between the current study and that of Delagarde *et al.* (2011b) (RPE = 16%), using also GrazeIn for PDMI estimation, may be attributed to they managed a database containing data from twenty experiments conducted across five institutions, by different research teams, using different methods to estimate PDMI. The

data in the database used in the current study were only from one trial conducted under controlled conditions by one institution to simulate four grazing scenarios (testing only two factors: CD and SR). O'Neill *et al.* (2012a) also used a controlled dataset from three research dairy cow farms located in Ireland within 6.5 km of each other; methods and equipment used during their studies were similar and PDMI was estimated using only the n-alkane technique (being RPE = 12% in that study similar to the one in ours).

When the source of error in the prediction was investigated under Galician conditions, the line bias as a proportion of the MSPE was low indicating an adequate structure of GrazeIn for PDMI prediction (Delagarde *et al.*, 2011b; O'Neill *et al.*, 2012a). The random variation proportion of the MSPE was high, suggesting that the error was mainly due to random variation rather than a consistent bias. This agrees with Delagarde *et al.* (2011b) and O'Neill *et al.* (2012a) who reported similar MSPE proportions of error to those found in the current study. When the database in our study was broken into the different grazing scenarios investigated and GrazeIn was evaluated for PDMI prediction at herd by paddock level for each CD, the RPE was lower in middle than in early CD to that found at a total database level demonstrating that GrazeIn seem to have better accuracy for predicting in middle than in early CD. The most part of the MSPE in middle CD was accounted for by random variation (0.99). The highest RPE value was found in the EM herd, which showed the lowest proportion of random variation (0.82). In relation to that, Faverdin *et al.* (2011) reported that GrazeIn is accurate for MY prediction in cows at middle and late lactation but it could be improved in cows at early lactation. To achieve it, they suggested to focus on a better prediction of the mobilization of cows' body reserves.

Delagarde *et al.* (2011b) proposed various possibilities for increasing the accuracy of GrazeIn for prediction of PDMI. Between them, the first option would be to improve the current equations, parameters and/or algorithms for pasture growth and grazing management. The second possibility would be to include in the model other factors which affect PDMI as the environment from the current study (weather conditions and soil fertility), the accumulation of patches of pasture rejected when the grazing season progresses, the nutritive value of the selected pasture instead of that of offered pasture, and the pasture DM concentration. The morphological composition of the sward, *i.e.* leaf/stem ratio or dead/green material ratio, is not directly an input variable of GrazeIn. However, it is implicitly considered through its effect on pasture IVOMD and, thus, its FV. Although probable, a specific effect of the leaf/stem ratio on dai-

ly PDMI, at constant IVOMD, constant HM and constant DHA (all factors already considered), cannot be predicted from the available literature. In any case, the benefits of including new variables in the model should be only considered if gains in prediction accuracy for PDMI determination are got. A good compromise between simplicity and estimation should be found.

Milk yield prediction

The overall accuracy of GrazeIn for MY prediction in the current study is the same to that reported by O'Neill *et al.* (2012b) at herd by cow level (17%). Apart from that study, there are only a few other PDMI models that predict MY as an output (Freer *et al.*, 1997; Baudracco *et al.*, 2010). In fact, the evaluation of prediction models for MY at grazing is almost non-existent except for the evaluations carried out by Delagarde *et al.* (2011b) and O'Neill *et al.* (2012a) at herd by paddock level, using also the GrazeIn model, being the RPE values slightly lower in O'Neill's *et al.* (2012a) study (13%) than in Delagarde's *et al.* (2011b) study (14.0%). A comparison between the prediction accuracy of GrazeIn from O'Neill's *et al.* studies (2012a,b) show that RPE values are slightly lower for PDMI than for MY whatever the data are investigated at herd by paddock level or either at herd by cow level.

GrazeIn predicted MY in early CD with lower levels of error in comparison to MY predicted in middle CD for all cows in the current study. This agrees with results of O'Neill *et al.* (2012b), who found lower levels of error in MY predicted with cows at early or middle lactation compared to those in late lactation. Results from O'Neill *et al.* (2012b) show that in late lactation, a large proportion of the MSPE (0.41) came from the mean bias indicating that the model was not robust for MY prediction. From this evaluation, it seems that the over-prediction of MY in EH herd (RPE = 20.4%) may be attributed to the lactation curve (due to not being well-adapted to cows at early CD managed at high SR). Delagarde *et al.* (2011b) also found an over-prediction of MY by using GrazeIn, but they did not investigate this over-prediction of MY by stage of lactation. It seems that the persistency of the PMY_{peak} curve is too high resulting in over-prediction of MY in cows on EH herd. The PMY_{peak} curve is theoretical and so cannot be validated, as grazing cows are never fed to optimum levels throughout the entire lactation (Faverdin *et al.*, 2011). The theoretical curve used in the GrazeIn model was derived using French data. O'Neill *et al.* (2012b) suggested that it might be appropriate to derive a theoretical curve using data from cows of the country in question to be more accurate in the prediction of MY. The results also indicate that adjusting early CD

to medium SR may be an effective strategy for grazing dairy cows to align animal requirements and pasture supply for getting high total DM intake and MY.

From the results of the current experiment, it is concluded that GrazeIn predicted PDMI at paddock level and MY at cow level in a realistic manner over a wide range of grazing scenarios in which four herds of cows were managed and two main factors were investigated (calving date and stocking rate). Considering that the error of prediction for all herds was good or acceptable, with PDMI close to 10% and MY lower than 20%, might be recommended to use this model as a suitable tool for decision support systems to help dairy farmers gain confidence on pasture-based milk production systems. Nevertheless, further studies should be conducted to improve the prediction accuracy of GrazeIn by testing more complex grazing scenarios adapted to an even larger range of situations.

Acknowledgements

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