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Herbage dry matter intake estimation of grazing dairy cows based on animal, behavioral, environmental, and feed variables

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ABSTRACT

Information about the individual herbage DMI (HDMI) of grazing dairy cows is important for an efficient use of pasture herbage as an animal feed with a range of benefits. Estimating HDMI, with its multifaceted influencing variables, is difficult but may be attempted using animal, performance, behavior, and feed variables. In our study, 2 types of approaches were explored: 1 for HDMI estimation under a global approach (GA), where all variables measured in the 4 underlying experiments were used for model development, and 1 for HDMI estimation in an approach without information about the amount of supplements fed in the barn (WSB). The accuracy of these models was assessed. The underlying data set was developed from 4 experiments with 52 GA and 50 WSB variables and one hundred thirty 7-d measurements. The experiments differed in pasture size, herbage allowance, pregrazing herbage mass, supplements fed in the barn, and sward composition. In all the experiments, cow behavioral characteristics were recorded using the RumiWatch system (Itin and Hoch GmbH, Liestal, Switzerland). Herbage intake was estimated by applying the n-alkane method. Finally, HDMI estimation models with a minimal relative prediction error of 11.1% for use under GA and 13.2% for use under WSB were developed. The variables retained for the GA model with the highest accuracy, determined through various selection steps, were herbage crude protein, chopped whole-plant corn silage intake in the barn, protein supplement or concentrate intake in the barn, body weight, milk yield, milk protein, milk lactose, lactation number, postgrazing herbage mass, and bite rate performed at pasture. Instead of the omitted amounts of feed intake in the barn and, due to the statistical procedure for model reduction, the unconsidered variables postgrazing herbage mass and bite rate performed at pasture, the WSB model with the highest accuracy retained additional variables. The additional variables were total eating chews performed at pasture and in the barn, total eating time performed at pasture, number of total prehension bites, number of prehension bites performed at pasture, and herbage ash concentration. Even though behavioral characteristics alone did not allow a sufficiently accurate individual HDMI estimation, their inclusion under WSB improved estimation accuracy and represented the most valid variables for the HDMI estimation under WSB. Under GA, the inclusion of behavioral characteristics in the HDMI estimation models did not reduce the root mean squared prediction error. Finally, further adaptation, as well as validation on a more comprehensive data set and the inclusion of variables excluded in this study such as body condition score or gestation, should be considered in the development of HDMI estimation models.

Key words: dairy cow, herbage intake estimation, mastication, pasture, prehension

INTRODUCTION

In addition to a better consumer image (Getter et al., 2015), improved animal welfare (Arnott et al., 2017), and higher product quality (O'Callaghan et al., 2016), grazing dairy cows offer potential ecological (Guyader et al., 2016) and economic (Holshof et al., 2015) benefits. However, recent estimates have shown that only 49 to 52% of lactating dairy cows in European countries have access to pasture, and the numbers have been declining in recent years (Van den Pol et al., 2015). Although pasture herbage has widely been identified as the cheapest source of nutrients for dairy cows (Peyraud et al., 2001), the decline in grazing may be the result of larger herds, fragmentation or lack of land, development of automatic milking systems, and farmer expectations regarding productivity in a pasture-based system, as mentioned by Kristensen et al. (2010). Information about individual herbage DMI (**HDMI**) allows estimating the nutrient supply from pastures and determining an adapted optional supplementation in the barn that may improve efficiency and lead to higher

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acceptance in practice. Furthermore, information about intake compared with production can be used to assess the nutrient and energy efficiency of individual grazing dairy cows and may enable selection for this trait. Several methods for HDMI estimation exist. These include measuring herbage mass or sward surface height before and after grazing, back calculation from the energy requirements of the cows and the energy density of the offered herbage, near-infrared reflectance spectroscopy, and marker techniques (Decruyenaere et al., 2009). However, these techniques are expensive, time consuming, and impracticable at the farm level and yield only group- or herd-mean HDMI estimations. Behavioral characteristics may also be considered in estimating the individual animal HDMI (Andriamandroso et al., 2016). Oudshoorn et al. (2013) calculated grass intake using regressions based on grazing time and animal individual bite frequency. Various methods based on jaw switches, pressure sensors, microphones, accelerometers, and electromyography have been developed to record behavioral characteristics automatically. Among these, pressure sensors and microphones can detect jaw movements with high accuracy (Andriamandroso et al., 2016). Because the RumiWatch system (**RWS**; Itin and Hoch GmbH, Liestal, Switzerland), based on a pressure sensor and a triaxial accelerometer, showed reliable accuracy in detecting eating and rumination behavior (Ruuska et al., 2016; Rombach et al., 2018), it was chosen for the present investigation. However, eating chews or prehension bites alone seem insufficient to estimate HDMI, and they explain only a minor part of HDMI variation. Therefore, in addition to behavioral characteristics, Decruyenaere et al. (2009) mentioned animal and feed characteristics that might have an influence on the HDMI of grazing ruminants. Timmer et al. (2016) showed a reliable estimation of HDMI using behavioral as well as animal- and herbage-related variables in the HDMI estimation model. In our study, we built models for HDMI estimation based on 2 approaches using the RWS, which can differentiate between mastication chews and prehension bites. Data from 4 experiments were used. The data contained differences in farm management, pasture size, grazing duration, herbage allowance, pregrazing herbage mass, supplements fed in the barn, and sward composition. The main objective of our study was to develop models for HDMI estimation based on the merged data set of the 4 experiments mentioned above. First, a global approach (**GA**) was explored, where all measured variables were used for the model development. Then, a second approach was investigated without the information about the supplemented amounts of forage or concentrate in the barn (referred to as **WSB**). Finally, we studied the effect of behavioral characteristics recorded with the RWS on the accuracy of the HDMI estimation under both approaches.

MATERIALS AND METHODS

Experimental Design, Animals, and Housing

Three grazing experiments were conducted at the Agroscope experimental farm in Posieux, Switzerland, and 1 was conducted at the Ferme-Ecole in Sorens, Switzerland, from 2014 to 2016 (Table 1). All experimental procedures were in accordance with Swiss guidelines for animal welfare and were approved by the Animal Care Committee of the Canton Fribourg, Switzerland (no. 2014_38_FR, 2014_51_FR, 2015_11_FR, and 2015_22_FR). Before selection of the experimental cows, all cows passed a medical check. In general, each period consisted of 2 wk of adaptation to adjust pasture-accustomed cows to the various feeding treatments and measuring devices followed by 1 wk of data collection. Consequently, the experiments lasted 21 to 63 d. Between 18 and 28 Holstein and Red Holstein cows were used in the experiments. The experimental cows were distributed equally across the experimental groups based on BW, milk yield, DIM, and lactation number. At the beginning of the experiments, the cows had an average BW of 601 ± 58.7 kg, were 155 ± 64.5 DIM, were in lactation 2.5 ± 1.75 on average, and produced 24.2 ± 5.18 kg of milk/d (±SD).

In all 4 experiments, the paddocks were grazed rotationally, and the stocking periods lasted 1 to 3 d. All cows grazed day and night between 16 and 19 h/d depending on the experiment. In the meantime, the cows were kept in freestall barns and were supplemented if intended as part of the treatment structure. In addition, they were milked, milk was sampled, and alkane marker capsules were administered. On average, the pastures (permanent and sown) comprised grasses (mainly *Lolium perenne*, *Poa pratensis*, and *Lolium multiflorum*; 58–84% of the fresh herbage biomass), legumes (*Trifolium repens* and *Trifolium pratense*; 6–26% of the fresh herbage biomass), and forbs (mainly *Taraxacum officinale*, *Plantago lanceolata*, and *Rumex acetosa*; 2–29% of the fresh herbage biomass).

The first experiment (**EX1**) was organized as a crossover block design with 3 treatments and 3 periods (Table 1). All experimental cows in EX1 grazed as a single group in the same paddocks. Two out of 3 experimental groups were supplemented in the barn at weighing troughs (Insentec B.V., Marknesse, the Netherlands) with either 10 kg DM/d of chopped whole-plant corn silage or with 8.2 kg DM/d of chopped whole-plant corn silage mixed with 1.8 kg DM/d of protein concentrate (60% expeller soybean meal, 25%

Table 1. Basic data of the 4 experiments

Item	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Period	Jul. 28–Sep. 27, 2014	May 18–Jun. 7, 2015	Aug. 31–Sep. 20, 2015	Jun. 27–Jul. 17, 2016
Data sets in database (no.)	54	28	24	24
Experimental design	Crossover block	Balanced block	Balanced block	Balanced block
Treatment × period	3 × 3	2 × 1	2 × 1	2 × 1
Animals (no.)	18	28	24	24
Pasture size[1] (ha)	0.30	0.90	0.41, 0.06	0.21, 0.17
Herbage allowance (kg of DM/d)	21.4	26.6	21.9	18.1, 14.9
Supplement[2]	NSP, corn, corn protein	NSP, concentrate	NSP	NSP, corn
Farm management	Conventional	Organic	Conventional	Conventional
Primiparous cows (%)	30.0	64.3	41.7	25.0
Cow genetics[3]	CH	CH, NZ	CH	CH
Outdoor temperature (°C)	14.8 (min. 10.0, max. 19.9)[4]	20.2 (min. 13.7, max. 26.7)	12.9 (min. 6.8, max. 19.2)	15.1 (min. 10.1, max.19.7)
Daily precipitation (mm)	6 (min. 0.1, max. 11)	0.5 (min. 0.1, max. 2.7)	9.6 (min. 0.1, max. 30.9)	12.1 (min. 0.2, max. 15.3)
Reference	Rombach et al. (2018)	Schori et al. (unpublished data)	Rombach et al. (unpublished data)	Menzi et al. (unpublished data)

[1]Experiments 1 and 2: all experimental cows grazed together in the same paddocks; experiments 3 and 4: the 2 experimental groups grazed on 2 paddocks.

[2]NSP = not supplemented in the barn; corn = supplemented in the barn with chopped whole-plant corn silage; corn protein = supplemented in the barn with chopped whole-plant corn silage and with protein concentrate; concentrate = supplemented in the barn with concentrate (UFA 275; UFA AG, Herzogenbuchsee, Switzerland).

[3]CH = Swiss Holstein; NZ = New Zealand Holstein.

[4]min. = minimum; max. = maximum.

corn gluten, 10% potato protein, and 5% dried sugar beet pulp). The third group was not supplemented. Each cow served as its own control and underwent all 3 treatments. The second (**EX2**), third (**EX3**), and fourth (**EX4**) experiments were performed as balanced block designs including 2 treatments and 1 period. In EX2, 1 group was supplemented with an average of 3 kg DM/d of concentrate (UFA 275; UFA AG, Herzogenbuchsee, Switzerland) through an automatic concentrate feeder in the barn. The other group received no concentrate. All experimental cows in EX2 grazed as a single group in the same paddocks. In EX3, one group of cows grazed on swards with a high herbage mass of 2,288 kg of DM/ha, and the other group grazed on swards with a low herbage mass of 589 kg of DM/ha. The cows in both groups had a similar herbage allowance of approximately 22 kg of DM/d per cow and were not supplemented in the barn. In EX3 and EX4, the cows from each group grazed on different paddocks. One experimental group in EX4 was supplemented in the barn at the weighing troughs (Insentec B.V.) with 4 kg DM/d of chopped whole-plant corn silage. The other group received no supplementation. The chemical composition of the herbage and the supplements fed during the experimental periods are shown in Tables 2 and 3. The cows had free access to drinking water during all experiments. The ambient outdoor temperature and the amount of rainfall during the experiments were recorded daily at the meteorological station in Grangeneuve (Meteo-Schweiz, Station Posieux, Switzerland).

Data Recording and Sample Collection

The sward height was measured daily in all experiments using an electronic rising plate meter (Jenquip, Feilding, New Zealand; 1 click unit = 0.5 cm; EX1, EX3, and EX4) or a C-Dax Pasture Meter (C-Dax Ltd., Palmerston North, New Zealand; EX2). Herbage mass was measured before and after grazing each paddock by cutting 2 strips (1 m wide × 9.4 ± 3.02 (SD) m long; >6.7 click units or 3.35-cm stubble height) with a sickle-bar mower (Rekord 38, Bucher Landtechnik AG, Niederweningen, Switzerland). The herbage mass of the cut strips and the analyzed herbage DM content were used to calculate the herbage mass.

The RWS, consisting of the RumiWatch Halter (**RWH**; Itin and Hoch GmbH) and the RumiWatch Converter 0.7.3.31 (Itin and Hoch GmbH), was used in all experiments to record and evaluate the behavioral characteristics of the experimental cows. Further details about the RWS, the accuracy and definition of the recorded behavioral characteristics, and the setup and handling of the RWH have been described previously (Rombach et al., 2018). To accustom the cows to the

Table 2. Chemical composition of the herbage grazed during the 4 experiments

Item	Experiment 1						Experiment 2		Experiment 3[1]				Experiment 4[2]			
	Period 1		Period 2		Period 3				Low		High		NSP		SP	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DM (g/kg of wet weight)	149	25.7	152	28.1	157	26.6	218	26.9	174	30.2	167	22.0	200	41.2	201	41.6
Analyzed nutrient composition (g/kg of DM)																
OM	887	8.6	891	7.2	889	8.1	900	7.1	902	4.1	902	3.1	908	2.1	907	4.9
CP	169	15.4	215	9.6	212	6.8	158	22.8	240	26.4	184	9.9	179	8.4	165	14.8
ADFom[3]	261	18.7	206	11.1	191	5.7	221	27.6	188	13.5	218	10.9	239	13.3	245	18.5
NDFom[4]	418	71.6	334	19.2	301	18.1	405	55.4	328	28.2	359	17.7	428	31.5	441	41.2
Crude fiber	187	19.8	180	18.8	192	21.1	209	26.0	167	12.9	195	8.8	218	11.9	229	11.9
Calculated energy and APDE[5] content[6] (per kg of DM)																
NE_L (MJ)	6.0	0.22	6.5	0.07	6.5	0.08	6.1	0.33	6.6	0.14	6.3	0.07	6.2	0.09	6.1	0.15
ADPE (g)	103	4.5	115	2.3	115	1.8	101	6.9	118	4.0	107	1.6	106	2.0	103	3.7
Analyzed n-alkane content (mg/kg of DM)																
HC32[7]	5.7	0.71	5.4	0.49	4.8	0.22	3.4	0.70	6.7	0.59	6.3	0.51	4.6	0.35	5.6	0.31
HC33[8]	72.4	5.35	66.8	4.81	65.2	4.11	47.1	6.48	87.4	9.97	83.7	8.68	77.9	6.93	93.4	8.16

[1]Low = group that grazed on swards with a sward height of 10 click units and an herbage mass of 589 kg of DM/ha; High = group that grazed on swards with a sward height of 18 click units and an herbage mass of 2,288 kg of DM/ha.

[2]NSP = not supplemented in the barn; SP = supplemented in the barn with 4 kg of DM/d of chopped whole-plant corn silage.

[3]ADF corrected for residual ash.

[4]NDF corrected for residual ash.

[5]Absorbable protein in the small intestine when rumen-fermentable energy is limiting microbial protein synthesis in the rumen.

[6]According to Agroscope (2015).

[7]Dotriacontane ($C_{32}H_{66}$).

[8]Tritriacontane ($C_{33}H_{68}$).

Table 3. Average chemical composition of the supplements fed during the experiments

Item	Experiment 1[1]						Experiment 2		Experiment 4	
	CS		Protein		CS + protein		Concentrate[2]		CS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DM (g/kg of wet weight)	398	33.8	882	23.9	485	32.0	885	—	405	3.4
Analyzed nutrient composition (g/kg of DM)										
OM	971	0.5	943	0.2	966	0.4	946	—	975	1.0
CP	72	5.7	562	6.6	160	5.9	115		89	3.2
ADFom[3]	194	29.3	76	3.0	173	24.6	73	—	206	10.5
NDFom[4]	351	49.7	316	34.8	345	41.0	195	—	389	25.0
Crude fiber	163	23.8	34	0.1	140	19.5	47	—	164	22.1
Calculated energy and APDE[5] content[6] (per kg of DM)										
NE_L (MJ)	6.9	0.24	7.5	—	7.2	0.20	7.0	—	7.0	0.17
APDE (g)	70	3.74	295	—	111	3.07	85	—	74	0.82
Analyzed n-alkane content (mg/kg of DM)										
HC32[7]	1.1	0.21	1.3	1.22	1.1	0.21	ND[8]	—	0.8	0.03
HC33[9]	9.7	1.43	0.4	0.27	8.0	1.23	1.7	—	10.4	0.82

[1]CS = chopped whole-plant corn silage; Protein = protein concentrate consisting of (as-fed basis) 60% expeller soybean meal, 25% corn gluten, 10% potato protein, and 5% dried sugar beet pulp.

[2]Commercial concentrate (UFA 275; UFA AG, Herzogenbuchsee, Switzerland).

[3]ADF corrected for residual ash.

[4]NDF corrected for residual ash.

[5]Absorbable protein in the small intestine when rumen-fermentable energy is limiting microbial protein synthesis in the rumen.

[6]According to Agroscope (2015).

[7]Dotriacontane ($C_{32}H_{66}$).

[8]Not detected.

[9]Tritriacontane ($C_{33}H_{68}$).

measuring system, the RWH were attached to the cows 4 d before the start of each measuring week and left on throughout the week. In EX1, 15 cows were equipped with version 3.0 of the RWH and 3 cows were equipped with version 6.0. These differ in materials, adjustability, and wearing comfort. In EX2, EX3, and EX4, all cows were equipped with RWH version 6.0. The recorded raw data were read through the interface software RumiWatch Manager (version 2.1.0.0; Itin and Hoch GmbH) and processed using the evaluation software RumiWatch Converter (version 0.7.3.31). Compared with the converters used in Rombach et al. (2018), RumiWatch Converter 0.7.3.31 allows a differentiation of other bites, mastication chews with the head up, mastication chews with the head down, prehension bites, and time spent masticating and eating.

Milk yield was measured twice daily during the milkings in the milking parlor (EX1, EX3, EX4: Fullwood, Arnold Bertschy AG, Guschelmuth, Switzerland; EX2: MidiLine, DeLaval AG, Sursee, Switzerland) with a Pulsameter (EX1, EX3, EX4: LMS GmbH Stützerbach, Ilmenau, Germany) or an MM15 (EX2: DeLaval AG). Milk composition was measured for EX1, EX2, and EX4 on d 2 and 5 and for EX3 on d 2, 4, and 6 during the measuring week. Aliquots of subsamples from the morning and evening milkings were pooled and preserved in 1 sample tube containing a Broad-Spectrum Microtab II (Gerber Instruments AG, Effretikon, Switzerland) and stored at 8°C for subsequent analysis of milk fat, protein, lactose, and casein content. After each milking, BW was measured with an animal weighing system (EX1, EX3, EX4: Ga5010, Insentec B.V.; EX2: W-2000, DeLaval AG).

Individual HDMI was estimated using the n-alkane double indicator method (Mayes et al., 1986). Six days before each measuring week until the next-to-last day of the measuring weeks, cows were dosed twice daily with 1 gelatine capsule (HGK-17-60 sl; Capsula GmbH, Ratingen, Germany) containing 0.5 g of dotriacontane ($C_{32}H_{66}$, **HC32**; Minakem Beuvry Production S.A.S., Beuvry la Forêt, France) as the external alkane marker on a carrier of 4.5 g of dried fruit pomace. During 7 d, once per day after the morning milking, feces of each cow were spot-sampled indoors to determine the content of alkanes in the feces. Samples were taken from spontaneous defecations or with mild stimuli, pooled for each cow and measuring week, and stored at −20°C for further analysis. To determine the content of alkanes in the herbage eaten by the cows, herbage collection was carried out 7 d, in the morning and afternoon. By following the experimental cows one after another and observing their grazing selection, small samples of the most likely grazed herbage were cut with a battery grass shearer (Gardena; Husqvarna Schweiz AG, Mägenwil, Switzerland). The herbage sampling started 24 h before the feces sampling and ended 24 h earlier. These samples were chopped and stored at −20°C for further analysis.

Laboratory Analysis

Milk samples were analyzed using Fourier-transform mid-infrared spectrometry (Combi-Foss FT +; Foss, Hillerød, Denmark) to determine fat, protein, casein, and lactose content. Fluorescence flow cytometry (Fossomatic FC200; Foss) was used to count the number of somatic cells in the milk samples.

The herbage and supplement samples, except the protein supplement in EX1 and concentrate supplement in EX2, were stored at −20°C until they were lyophilized (Delta 1-24 LSC; Christ, Osterode, Germany). Subsequently, all samples, including protein and concentrate supplements, were milled through a 1.0-mm screen (Brabender mill with titanium blades; Brabender GmbH & Co. KG, Duisburg, Germany), dried for 3 h at 105°C to determine DM, and finally incinerated at 550°C until a stable mass was reached to determine the ash content (AOAC International, 1995; method 942.05). Mineral residues in the ash were dissolved by nitric acid and analyzed for Ca, P, Na, Mg, and K with inductively coupled plasma optical emission spectrometry (ICP-OES Optima 7300 DV; PerkinElmer, Waltham, MA) based on ISO (2009; method 27085). The contents of the HC32 and tritriacontane ($C_{33}H_{68}$) were analyzed as described by Thanner et al. (2014). The N content of herbage and supplement samples was analyzed using the Dumas method (ISO, 2008; method 16634-1) on a C/N analyzer (Trumac CNS; Leco Instruments, St. Joseph, MI); the results were multiplied by 6.25 to obtain the CP content. The contents of ADF (AOAC International, 1995; method 973.18), NDF (AOAC International, 1995; method 2002.4), and crude fiber (AOAC International, 1995; method 978.10) for the herbage and supplement samples were analyzed with Gerhardt Fibertherm (Gerhardt GmbH & Co. KG, Königswinter, Germany). The NDF and ADF contents were separately determined (parallel). For NDF analysis, heat-stable amylase and sodium sulfite were added. A correction for the residual ash obtained after 2 h of incineration at 550°C was made for ADF corrected for residual ash and NDF corrected for residual ash.

Calculations and Data Analysis

The NE_L content of herbage was calculated from chemical composition according to Agroscope (2015). For chopped whole-plant corn silage, NE_L content was calculated according to Agroscope (2006). Herbage intake calculation was based on equations proposed by Mayes et al. (1986). Equation 1 was used to calculate the daily HDMI of every single experimental cow in the 4 experiments:

$$\text{HDMI} = \frac{\dfrac{F_{33}}{F_{32}} \times \left\{ \begin{matrix} \left[A_{32} + (P \times P_{32}) + (CN \times CN_{32}) + (CR \times CR_{32})\right] \\ -\left(P \times P_{33} + CN \times CN_{33} + CR \times CR_{33}\right) \end{matrix} \right\}}{H_{33} - \dfrac{F_{33}}{F_{32}} \times H_{32}}, \quad [1]$$

where HDMI represents the daily HDMI (kg); F_{33}, H_{33}, P_{33}, CN_{33}, and CR_{33} are the concentrations of tritriacontane (mg/kg of DM) in feces, herbage, protein supplement, concentrate, and chopped whole-plant corn silage, respectively; F_{32}, H_{32}, P_{32}, CN_{32}, and CR_{32} are the concentrations of HC32 (mg/kg of DM) in feces, herbage, protein supplement, concentrate, and chopped whole-plant corn silage consumed, respectively; P, CN, and CR are the amounts (kg of DM/d) of consumed protein supplement, concentrate, and chopped whole-plant corn silage, respectively; and A_{32} is the daily dose of HC32 (mg/d) administered via the alkane capsules.

The weekly averages of pasture, herbage, intake, animal, milk, and behavioral data used for the development of the different HDMI estimation models are shown in Table 4. The HDMI estimated by the n-alkane double indicator method was used as the reference herbage intake on pasture for the development and validation of 4 approaches. First, a GA was explored, where all variables in the data set were used for the model development. Afterward, a WSB approach was investigated without information about the amount of the supplements fed in the barn; the variables whole-plant corn silage, protein supplement, and concentrate intake were removed from the data set for the model development. Finally, to study the benefits of behavioral characteristics as predictors for HDMI estimation, the behavioral characteristics recorded with the RWS were removed from the data set of the GA and the WSB. These approaches without RWS variables are hereafter referred to as **GAwRW** and **WSBwRW**, respectively.

Univariate and bivariate graphics and descriptive statistics were used to provide an overview of the data set. Linear dependencies between regression variables

Table 4. Mean (n = 109) and range of the pasture, intake, animal, milk, and behavioral characteristics used for the herbage DMI estimation models

Item	Mean	Minimum	Maximum	SD of mean
Pasture variables				
Postgrazing herbage mass (kg of DM/ha)	222	63	554	143.4
Pregrazing herbage mass (kg of DM/ha)	1,206	589	2,333	628.5
Residence time on pasture (h/d)	18	15	19	1.2
Herbage allowance (kg of DM/cow per d)	23.6	11.1	38.9	9.28
Herbage variables				
CP (g/kg of DM)	187	158	240	27.1
Ash (g/kg of DM)	102	92	122	9.1
Intake variables (kg/d)				
Herbage DMI	12.4	4.7	20.4	2.93
Protein or concentrate intake[1]	0.8	0.0	4.0	1.18
Corn silage intake[1,2]	3.7	0.0	7.9	3.08
Animal variables				
BW (kg)	610	428	719	58.3
Lactation number	2.7	1.0	9.0	1.92
Milk yield and content				
Milk yield (kg/d)	23.3	14.0	38.0	4.56
Fat (%)	4.1	2.7	5.6	0.57
Protein (%)	3.3	2.4	3.9	0.28
Lactose (%)	4.6	4.0	5.2	0.21
Daily behavioral characteristics				
Total eating time (min/d)	613	441	742	57.4
Prehension bites (no./d)	30,165	11,784	41,346	6,578.4
Total eating chews (no./d)	44,027	31,668	54,174	4,495.2
Bite rate (total eating bites/min)	72	62	80	3.5
Bite mass (DMI/prehension bites)	0.54	0.27	1.60	0.216
Daily behavioral characteristics performed at pasture				
Total eating time (min/d)	548	355	691	62.4
Prehension bites (no./d)	28,757	11,037	40,304	6,664.4
Total eating chews (no./d)	40,004	26,225	48,710	4,842.2
Bite rate (total eating bites/min)	73	62	81	3.7
Bite mass (herbage DMI/prehension bites)	0.47	0.26	1.04	0.136
Head down (min/d)	667	179	956	118.9

[1]Consumed in the barn.

[2]Chopped whole-plant corn silage.

were detected by Pearson correlation coefficients near or equal to 1 and prevented by the exclusion of redundant variables.

A preliminary set of predictive linear models was based on the combined results of various statistical approaches (principal component analysis; partial least squares; forward, backward, and sequential selection; and best subset regression) using Systat 13 (version 13.0; Systat Software, Chicago, IL) and R (R Core Team, 2016) packages Rcmdr (Fox, 2005, 2017; Fox and Bouchet-Valat, 2017), leaps (Lumley and Miller, 2017), and rms (Harrell, 2017).

Spearman correlation coefficients facilitated the identification of monotonous relations between the reference variable (HDMI) and the continuous or ordinal regressors. Principal component analysis using the Pearson and Spearman correlation matrices, partial least squares regression (including dummy variables for categorical factors), linear models (forward, backward, and sequential selection), canonical correlation, and finally best subset regression modeling was applied to identify variables that (from a statistical point of view) could be deleted from the set of regressors, leaving a list of potentially important predictor variables. The complete set of variables as well as the statistical findings were assessed, and variables were included or excluded based on the statistical findings, pertinent knowledge, and experience. The resulting combined set of 25 variables was still too large. Therefore, model reduction by the best subset regression approach was applied, and models with fewer than 14 variables were kept for the final validation. As the sample size was too small to keep an independent validation set, the bootstrap validation method proposed by Harrell (2015) and implemented in the R function rms:validate .ols (Harrell, 2017) was used. This function combines modeling, model reduction, and bootstrap validation. The root mean squared prediction error (**RMSPE**) calculation was based on the results of 5,000 bootstrap samples (Efron and Hastie, 2016) to identify the optimal predictive model while still preventing overfitting. Moreover, the bootstrap validation method was

Table 5. Evaluated linear model GA7 for herbage DMI estimation for use under a global approach

Item	Coefficient	SE	β[1]	95% CI Lower	95% CI Upper	P-value
Model mean μ	11.27	6.182	0	−0.9954	23.5393	0.071
Protein or concentrate intake (kg of DM/d)	−1.09	0.153	−0.393	−1.3944	−0.7865	<0.001
Corn silage intake (kg of DM/d)	−0.64	0.047	−0.646	−0.7369	−0.5497	<0.001
Milk lactose (%)	−2.52	0.740	−0.187	−3.9876	−1.0497	<0.001
Lactation number	−0.29	0.091	−0.191	−0.46686	−0.1055	0.002
Herbage CP (g/kg of DM)	−0.03	0.006	−0.265	−0.0388	−0.0150	<0.001
Postgrazing herbage mass (kg of DM/ha)	−0.004	0.0010	−0.180	−0.0056	−0.0015	<0.001
Bite rate[2] (total eating bites/min)	−0.08	0.038	−0.101	−0.1514	−0.0015	0.046
BW (kg)	0.008	0.0034	0.170	0.0012	0.0148	0.021
Milk protein (%)	4.24	0.595	0.410	3.0599	5.4208	<0.001
Milk yield (kg/d)	0.35	0.037	0.570	0.2786	0.4272	<0.001

[1]Standardized coefficient; helps classify the variables according to their effect on the corresponding herbage DMI estimation model.

[2]Performed at pasture.

enhanced by including the optimism bias to prevent an underestimation of the RMSPE. Equation 2 shows the multiple linear regression structure of the HDMI estimation models:

$$y = \mu + (V1 \times C1) + (V2 \times C2) + \ldots + (Vn \times Cn), \quad [2]$$

where y represents the average daily HDMI (kg/cow) over 1 wk; μ is the model mean; and $V1$, $V2$, . . ., Vn are the explanatory variables with the corresponding coefficients $C1$, $C2$, . . ., Cn.

RESULTS

A data set of 130 measurements taken over 7 d consisting of 52 variables for GA and 50 variables for WSB (without protein supplement or concentrate and chopped whole-plant corn silage intake) was the database for the development and validation of the HDMI estimation models. For the development and validation of the WSBwRW and GAwRW HDMI estimation models, the data sets consisted of 42 variables for GAwRW (without 10 behavioral characteristics) and 40 variables for WSBwRW (without 10 behavioral characteristics and without protein supplement or concentrate and chopped whole-plant corn silage intake), and 130 measurements taken over 7 d were used. Due to technical difficulties with the RWH, in particular liquid leakage in the pressure sensor tubes, 21 (16%) of the records could not be correctly evaluated over the whole measuring week and were therefore not used for further model development and validation if behavioral characteristics were used in the HDMI estimation models. Thus, the final data set for GA and WSB model development consisted of 109 measurements.

HDMI Estimation Under a GA

The model with the lowest RMSPE for HDMI estimation under GA without overfitting (eliminating the nonsignificant variables) was model GA7 (Table 5). In this model, according to the β value (used to classify the variables and their effect on the HDMI estimation models), intake of chopped whole-plant corn silage [$P < 0.001$; standardized coefficient (β) = −0.646] showed the greatest effect on the target variable (HDMI), followed by milk yield ($P < 0.001$, β = 0.570), milk protein content ($P < 0.001$, β = 0.410), intake of protein supplement or concentrate ($P < 0.001$, β = −0.393), herbage CP ($P < 0.001$, β = −0.265), lactation number ($P = 0.002$, β = −0.191), milk lactose content ($P < 0.001$, β = −0.187), postgrazing herbage mass ($P < 0.001$, β = −0.180), BW ($P = 0.021$, β = 0.170), and bite rate performed at pasture ($P = 0.046$, β = −0.101).

HDMI Estimation Model Under an Approach Without Knowledge of the Supplements Fed

The model with the lowest RMSPE for HDMI estimation under WSB without overfitting (eliminating the nonsignificant variables) was model WSB8 (Table 6). In this model, according to the β value, number of prehension bites performed at pasture ($P < 0.001$, β = 2.475) showed the greatest effect on HDMI, followed by number of prehension bites ($P = 0.002$, β = −1.994), total time spent eating on pasture ($P < 0.001$, β = 0.636), number of total eating chews ($P < 0.001$, β = −0.488), BW ($P = 0.001$, β = 0.265), milk lactose content ($P < 0.001$, β = −0.236), herbage ash ($P = 0.004$, β = 0.236), milk yield ($P = 0.004$, β = 0.216), herbage CP ($P = 0.003$, β = −0.209), lactation number ($P = 0.011$, β = −0.199), and milk protein content ($P = 0.014$, β = 0.172).

Validation of the HDMI Estimation Models

The models suggested for GA (GA1–GA7) showed an estimation accuracy [100% − relative prediction error (**RPE**)] of 86.9% (GA1), increasing by an average of 0.3% for every variable added to 88.9% for model GA7. Model GA7 explained 79% of the HDMI variation, with an RMSPE of 1.38 kg of DM/animal per day and an RPE of 11.1% (Table 7).

The models suggested for WSB (WSB1–WSB8) showed an estimation accuracy of 85.1% (WSB1), increasing by an average of 0.2% for every variable added to 86.8% for model WSB8. Furthermore, model WSB8 explained 70% of the HDMI variation, with an RMSPE of 1.64 kg of DM/animal per day and an RPE of 13.2% (Table 7).

The models suggested for GAwRW (GAwRW1–GAwRW7; detailed data not shown) showed an estimation accuracy of 86.9% (GAwRW1), increasing by an average of 0.2% for every variable added to 88.3% for model GAwRW7. Furthermore, the model for GAwRW7 explained 77% of the HDMI variation, with an RMSPE of 1.5 kg of DM/animal per day and an RPE of 11.7%.

The models suggested for the approaches without behavioral characteristics (WSBwRW1–WSBwRW8; detailed data not shown) exhibited an estimation accuracy of 81.9% (WSBwRW1), decreasing by an average of 0.03% for every variable added to 81.7% for model WSBwRW8. Furthermore, the model WSBwRW8 explained 45% of the HDMI variation, with an RMSPE of 2.3 kg of DM/animal per day and an RPE of 18.3%.

Figure 1 presents the RMSPE of the HDMI estimation models with and without behavioral characteristics (RWS variables). Models without information about supplementation and behavioral characteristics exhibit an RMSPE between 2.2 and 2.3 kg of DM/animal per day depending on the number of predictors in the model. Inclusion of behavioral characteristics reduced the error term by about 0.5 kg of DM/animal per day. If amounts of supplements fed in the barn were available for HDMI estimation, the error term decreased again about 0.3 kg of DM/animal per day to end at 1.3 to 1.6 kg of DM/animal per day. In this case, inclusion of behavioral information did not additionally reduce the RMSPE.

DISCUSSION

The range of the measured variables in the 4 experiments that constituted the data set of our study allowed for the development and validation of different models for HDMI estimation under GA (GA1–GA10), WSB (WSB1–WSB10), GAwRW, and WSBwRW.

HDMI Estimation Using the n-Alkane Method

Herbage DMI estimated with the n-alkane method was used as the reference for model development and validation. In earlier investigations with barn-fed dairy cows, compared with the weighed intake, DMI estimation using the n-alkane method showed a low mean deviation of 0.05 kg, and the estimated and weighed DMI were highly correlated ($R^2 = 0.93$) for pooled samples (Berry et al., 2000). In conditions that were similar to those in our study, Kaufmann et al. (2011) found a mean deviation between estimated and weighed DMI of 0.2 kg for cows fed in the barn with fresh herbage. No exact reference for the daily HDMI for individual animals exists under grazing conditions; thus, a genuine

Table 6. Evaluated linear model WSB8 for herbage DMI estimation for use under the approach without knowledge of the supplements fed

Item	Coefficient	SE	β[1]	95% CI Lower	95% CI Upper	*P*-value
Model mean μ	−1.01	7.730	0	−16.3488	14.3387	0.897
Milk lactose (%)	−3.18	0.868	−0.236	−4.9019	−1.4573	<0.001
Lactation number	−0.30	0.115	−0.199	−0.5278	−0.0701	0.011
Herbage CP (g/kg of DM)	−0.02	0.007	−0.209	−0.0353	0.0070	0.003
Total eating chews[2] (no./d)	−0.0003	0.00007	−0.488	−0.0005	−0.0002	<0.001
Total eating time[3] (min/d)	0.03	0.005	0.636	0.0186	0.039	<0.001
Prehension bites[2] (no./d)	−0.0009	0.00027	−1.994	−0.0014	−0.0003	0.002
Prehension bites[3] (no./d)	0.001	0.00027	2.475	0.0005	0.0016	<0.001
Milk protein (%)	1.78	0.712	0.172	0.3683	3.1930	0.014
Herbage ash (g/kg of DM)	0.10	0.034	0.236	0.0331	0.1667	0.004
Milk yield (kg/d)	0.13	0.045	0.216	0.0442	0.2236	0.004
BW (kg)	0.01	0.004	0.265	0.0052	0.0197	0.001

[1]Standardized coefficient; helps classify the variables according to their effect on the corresponding herbage DMI estimation model.

[2]Performed at pasture and in the barn.

[3]Performed at pasture.

Table 7. Structure and accuracy of the evaluated herbage DMI estimation models[1]

	GA										WSB									
Item	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Pasture variables																				
Postgrazing herbage mass (kg of DM/ha)				x	x	x	x	x	x	x										
Herbage variables (g/kg of DM)																				
CP			x	x	x	x	x	x	x	x						x	x	x	x	x
Ash														x	x	x	x	x	x	x
Intake variables (kg/d)																				
Chopped whole-plant corn silage intake[2]	x	x	x	x	x	x	x	x	x	x										
Protein or concentrate intake[2]	x	x	x	x	x	x	x	x	x	x										
Animal variables																				
BW (kg)		x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x
Lactation number					x	x	x	x	x	x					x	x	x	x	x	x
Milk yield and content																				
Milk yield (kg/d)	x	x	x	x	x	x	x	x	x	x							x	x	x	x
Fat (%)																			x	x
Protein (%)	x	x	x	x	x	x	x	x	x	x								x	x	x
Lactose (%)						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Daily behavioral characteristics																				
Total eating chews (no./d)									x	x	x	x	x	x	x	x	x	x	x	x
Total eating chews[3] (no./d)								x	x	x										
Bite rate (total eating bites/min)										x										
Bite rate[3] (total eating bites/min)							x	x	x	x										
Prehension bites (no./d)													x	x	x	x	x	x	x	x
Prehension bites[3] (no./d)											x	x	x	x	x	x	x	x	x	x
Total eating time[3] (min/d)											x	x	x	x	x	x	x	x	x	x
Head down time[3] (min/d)																				x
Accuracy of evaluated models																				
No.	130	130	130	130	130	130	109	109	109	109	109	109	109	109	109	109	109	109	109	106
Multiple R	0.85	0.86	0.86	0.87	0.88	0.88	0.90	0.90	0.91	0.91	0.79	0.81	0.82	0.83	0.83	0.84	0.84	0.85	0.86	0.86
Squared multiple R (R^2)	0.72	0.74	0.75	0.76	0.77	0.77	0.81	0.81	0.82	0.83	0.62	0.65	0.67	0.68	0.69	0.70	0.71	0.73	0.74	0.74

Continued

Table 7 (Continued). Structure and accuracy of the evaluated herbage DMI estimation models[1]

Item	GA										WSB									
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Adjusted squared multiple R^2[4]	0.71	0.73	0.73	0.74	0.75	0.75	0.79	0.79	0.80	0.80	0.60	0.63	0.65	0.66	0.66	0.67	0.68	0.70	0.71	0.71
Standard error of the estimate	1.58	1.54	1.52	1.49	1.47	1.46	1.31	1.31	1.28	1.26	1.80	1.72	1.69	1.66	1.65	1.63	1.60	1.56	1.54	1.54
RMSPE[5] (bootstrapping)	1.62	1.59	1.57	1.55	1.53	1.52	1.38	1.39	1.36	1.34	1.85	1.78	1.75	1.73	1.73	1.71	1.68	1.64	1.65	1.65
RPE[6]	13.1	12.8	12.7	12.5	12.3	12.3	11.1	11.2	11.0	10.8	14.9	14.4	14.1	14.0	14.0	13.8	13.5	13.2	13.3	13.3

[1]GA = global approach; WSB = approach without the information about the supplemented amounts of forage or concentrate in the barn.
[2]Consumed in the barn.
[3]Performed at pasture.
[4]Related to the number of variables and observations.
[5]Root mean squared prediction error.
[6]Relative prediction error.

validation of the n-alkane method is not possible. Nevertheless, the n-alkane method is commonly suggested as one of the best available techniques for individual HDMI estimation of grazing animals (Smit et al., 2005; Decruyenaere et al., 2009; Pérez-Ramírez et al., 2012). However, there are weak points that may impede an accurate HDMI estimation. Lippke (2002) mentioned the diurnal variation of the n-alkane concentration in feces as one possible source of variation. To prevent variations, we administered HC32 on an apple pomace carrier twice daily. A further challenge was the collection of a representative sample of the herbage eaten by the grazing dairy cows during the day, especially in multispecies swards. Grazing cows can select for certain plant groups and graze on layers that may contain different alkane concentrations (Dove and Mayes, 2005; Heublein et al., 2017). To minimize this risk, we took herbage samples twice daily by imitating the feed selection of almost each experimental cow on pasture and pooled these. To prevent varying alkane dosing, as mentioned by Smit et al. (2005), HC32 was not applied on feeds or concentrates; instead, capsules containing the exact intended amount of HC32 were administered twice daily with a bolus gun.

Comparing our HDMI results generated with the n-alkane method [11.9 ± 3.31 (SD) kg of HDMI], the reference method, with those obtained from estimation equations for grazing dairy cows proposed by Faverdin et al. (2007) using our data set [13.3 ± 3.72 (SD) kg of HDMI], an R^2 of 0.77 (y = 1.178 + 0.962x; standard error of estimate = 1.76) was obtained (Figure 2). This suggests an acceptable correlation and general accordance of our reference method for HDMI, as no genuine or much better method exists.

Variables Used for HDMI Estimation Models

Behavioral characteristics are useful for HDMI estimation in many cases, although the comparison of RMSPE of the GA and GAwRW models showed no improvement in accuracy of the HDMI estimation. The importance of behavioral characteristics for HDMI estimation is shown under an approach without knowledge of the supplements fed because total eating chews, total eating time performed at pasture, prehension bites performed on pasture, and total prehension bites represent the most important variables in the WSB models. Compared with the WSBwRW models, WSB models had a lower RMSPE on average by 0.58 kg/cow per day. Clearly, behavioral characteristics seem to improve the accuracy of HDMI estimation if information about the amount of supplements fed in the barn to pasture is lacking.

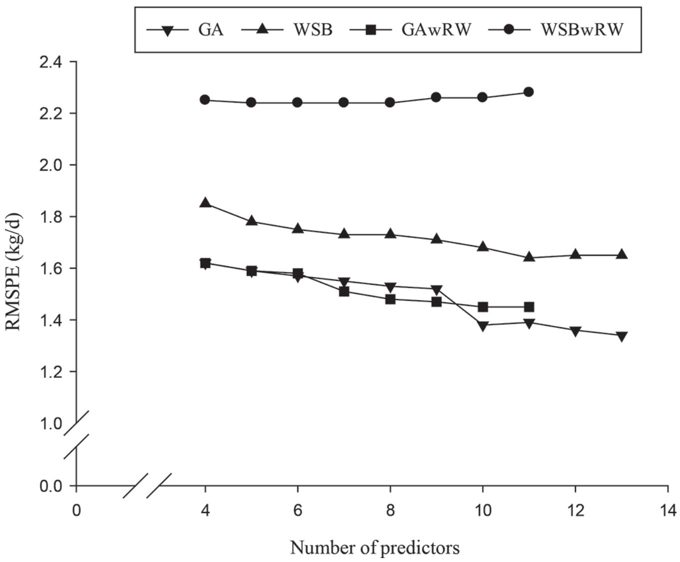

Figure 1. Comparison between the root mean squared prediction error (RMSPE) of the herbage DMI estimation models with or without behavioral characteristics in the data set for model development. GA = global approach; WSB = approach without the information about the supplemented amounts of forage or concentrate in the barn; GAwRW = GA without RumiWatch (Itin and Hoch GmbH, Liestal, Switzerland) system variables; WSBwRW = WSB without RumiWatch system variables.

Chacon et al. (1976) already concluded that herbage intake of grazing cattle can be estimated with reasonable precision using eating bites and bite size based on esophageal fistula samples. The challenge would be to know the bite size with intact animals. Later, Halachmi et al. (2016) investigated the effect of behavioral characteristics in DMI models for intact, TMR-fed cows housed in open, no-stall cowsheds. They found an improvement of 1.3 kg/cow per day on RMSPE,

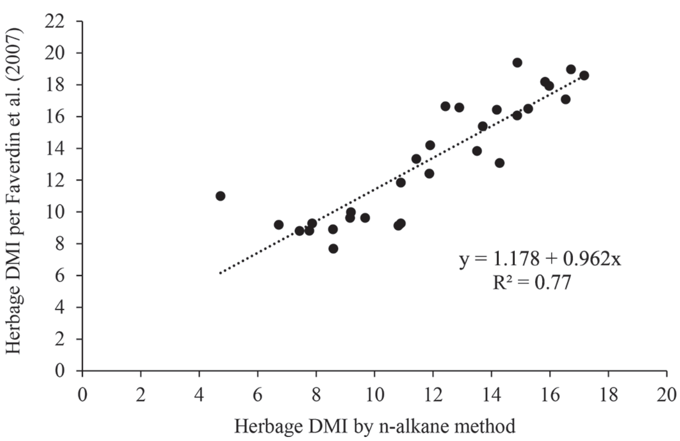

Figure 2. Comparison of our herbage DMI results generated with the n-alkane method and those obtained from estimation equations proposed by Faverdin et al. (2007; n = 30).

even greater than that in our study, when behavioral characteristics were incorporated in a DMI estimation model. Additional benefits of including behavioral characteristics in an intake estimation model might be the detection of sick or injured cows as well as cows in heat, as short-term feeding behavior is modified in characteristic ways in such cases (González et al., 2008). Andriamandroso et al. (2016) advocated the potential use of behavioral characteristics for HDMI estimation, as the bite is the elementary and indivisible unit of the whole grazing process. This is also seen in the present study, as according to β the variables prehension bites performed at pasture and total prehension bites were the 2 most important variables for the WSB models. An explanation for opposite effects of prehension bites performed at pasture and total prehension bites on HDMI might be the effect of supplements fed in the barn on HDMI (substitution of herbage); this also applies to the contrasting effects of total eating chews and total eating time at pasture.

Although behavioral characteristics represent the most important variables in the WSB model, a large variation in bite mass exists among animals, grazing, pasture, and feeding managements. Stated values range between 0.33 and 0.74 g of DM/bite (Barrett et al., 2001; Penning and Rutter, 2004). This leads to an insufficient correlation between behavioral characteristics and HDMI. According to Hellwing et al. (2015), grazing activity displays a close correlation with the predicted intake, yet further characteristics may have an influence on herbage intake. Therefore, in addition to behavioral data, animal, feed, grazing, and environmental variables must be included to reduce the estimation error of HDMI estimation models.

In our study, postgrazing herbage mass (222 kg of DM/ha; minimum: 63 kg of DM/ha; maximum: 554 kg of DM/ha) had a negative effect (−0.004 kg of DMI/d per kg of DM per ha) on HDMI. Contradicting results were found by O'Neill et al. (2013) with no or a positive effect of postgrazing sward height up to 0.99 kg of DMI/cm per day. As postgrazing sward height or postgrazing herbage mass are a function of pregrazing herbage mass and daily herbage allowance, differences in these factors as well as their interaction might have been partly the source of the contrasting results. Also, herbage CP content showed a negative effect on HDMI. This contradicts the findings of Timmer et al. (2016), who found a positive effect of milk urea content, which is associated with the intake of either CP or ruminally degraded CP. Results similar to those of Timmer et al. (2016) were found for milk protein content; thus, a higher HDMI is correlated with a higher milk protein content. Timmer et al. (2016) likewise found an effect of 3.79 kg of DMI/% of milk protein per day. The partially contradicting and partially similar results of our models and those of Timmer et al. (2016) might be caused by the interactions between the variables used, as discussed by Gruber et al. (2005).

Amounts of concentrate and protein supplement were merged into a single variable because the substitution rates are similar and lower than those for a forage supplement (chopped whole-plant corn silage; Delagarde and O'Donovan, 2005). The feeding of protein and concentrate supplements was associated with a decrease of HDMI in the GA model. O'Neill et al. (2013) observed a substitution rate of 0.58 to 0.71 kg of HDMI/kg of concentrate compared with our results (0.63 kg of HDMI/kg of concentrate). An even smaller reduction of 0.36 kg of HDMI/kg of concentrate was found for early-lactation dairy cows (McEvoy et al., 2009). The greater substitution rate in our studies could have been the result of a generous herbage allowance (Penno et al., 2006) in most of our studies. Thus, previous studies showed a substitution rate of zero for a high grazing pressure up to 0.6 to 0.8 for a low grazing pressure (Stockdale, 2000; Peyraud et al., 2001). Besides the generous herbage allowance, an increased amount of supplemented feed (Penno et al., 2006) or lactation stage could have had an influence; thus, cows in early lactation showed a lower substitution rate compared with cows in mid or late lactation (Penno et al., 2006). Furthermore, the substitution rate is greater when the quality of pasture allows cows to attain greater DMI from pasture alone (Penno et al., 2006).

Other reasons for the high substitution rate might be that the interaction between variables used in the models affected the coefficients, as discussed by Gruber et al. (2005), and maybe some bias due to different conditions between experiments. For example, the average of the calculated substitution rate between supplemented and not-supplemented pairs within experiments [0.63 ± 0.015 (SD) kg of HDMI/kg of concentrate or protein supplement] was lower compared with the coefficient of the explanatory variable protein and concentrate supplements (1.09 kg of DM/d) in GA7. The calculated substitution rate is similar to the findings of Stockdale (2000) and Peyraud et al. (2001). The decrease in HDMI caused by the supplementation of chopped whole-plant corn silage was smaller compared with that found for concentrate and protein supplementation. However, the coefficients (0.64 kg of DM/d) in this case are comparable with the calculated substitution rate [0.47 ± 0.015 (SD) kg of HDMI/kg of chopped whole-plant corn silage supplement]. Usually, substitution rates resulting from supplementing forage to pasture are greater than those from supplementing concentrates due to the greater forage fill (unité d'encombrement; Faverdin et al., 2007) value representing rumen fill (Delagarde and O'Donovan, 2005). Different experiments were used to calculate substitution rates. Varying environmental, feed, and animal characteristics may have therefore caused inconsistent substitution rates between concentrates and forage even though the individual substitution rates were in an expected range.

As a measure for body size and an indicator for rumen size, BW was positively correlated with HDMI in our study (i.e., an increase of 0.8 to 1 kg/100 kg of BW for our models). Similar increases of 0.95 and 1.3 kg/100 kg of BW were measured by Delagarde and O'Donovan (2005) and Gruber et al. (2005). A considerably greater increase in grass DMI, 2.0 kg/100 kg of BW (McEvoy et al., 2009), may be related to the early lactation stage of their cows compared with our study. Gruber et al. (2005) showed a greater increase in DMI per 100 kg of BW for cows in early lactation compared with cows in mid or late lactation.

Besides the physical feed intake capacity of the cow, proxied by BW, total DMI seems to be one driving force for milk production and vice versa, a conclusion that has been drawn in several other studies (Delagarde and O'Donovan, 2005; Gruber et al., 2005; McEvoy et al., 2009). The coefficient of the explanatory variable milk yield was between 0.13 (WSB8) and 0.35 (GA7) kg of HDMI/kg of milk per day. A reason for differences in the coefficients for milk yield between GA7 and WSB8 might be the aforementioned interaction between the variables used in the models.

Precision of the HDMI Estimation Models

The models GA7 and WSB8 showed the highest accuracy in estimating HDMI, with an R^2 of 0.81 and 0.73 and an RPE of 11.1 and 13.2%, respectively. The explained proportion of variation of the HDMI and the accuracy of these models are similar to those of other investigations. The models of McEvoy et al. (2009) accounted for 79% of the HDMI variation for early-lactating dairy cows, and those of Timmer et al. (2016) accounted for 84% of the HDMI variation. Delagarde and O'Donovan (2005) obtained an RPE between 10 and 25% for the HDMI of grazing dairy cows. Likewise, Keady et al. (2004) found an RPE for grass silage DMI between 10 and 20% for dairy cows fed indoors. Overall, the RPE of all of our models, developed for use under GA (RPE = 10.8–13.1%) as well as under WSB (RPE = 13.3–14.9%), showed an acceptable prediction of HDMI using detectable variables. Fuentes-Pila et al. (1996) suggested that an RPE value lower than 10% indicates a satisfactory prediction of the DMI, whereas an RPE between 10 and 20% indicates a relatively good or acceptable prediction, and an RPE greater than 20% indicates an unsatisfactory prediction. According to

Delagarde et al. (2011), a threshold for good intake estimation models for practical use should be a mean prediction error of 10%. Nevertheless, this threshold is hard to achieve, particularly for grazing dairy cows, as the available reference methods for development and validation of the HDMI estimation models are indirect methods. Furthermore, Galyean (2016) argued that daily intake of cattle is naturally variable, and Gruber et al. (2005) stated that a biologically determined natural scattering of about 10% might also impede the development of reliable intake estimation models.

CONCLUSIONS

With the HDMI estimation models developed in this study, HDMI could be estimated with an RPE between 11.1% (GA7) and 13.2% (WSB8) at best. When the amount of supplements fed was unknown, the inclusion of behavioral characteristics in the model showed a clear added value regarding the accuracy of the individual HDMI estimation. On the other hand, the inclusion of behavioral characteristics in the HDMI estimation model when amount of supplements fed was known did not significantly reduce the RMSPE. Finally, a larger data set (in terms of number of animals and herds and covering more breeds, different grazing systems, and management patterns, including, for example, varying supplementation) will be needed for further development and validation of a robust HDMI estimation model.

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