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Meta-analysis of the effect of pregrazing pasture mass on pasture intake, milk production, and grazing behavior of dairy cows strip-grazing temperate grasslands

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ABSTRACT

Grazing management is a key factor in pasture-based dairy systems, which can be improved given advanced knowledge of the effects of pregrazing pasture mass (PM) on the performance of dairy cows. The aim of this study was to quantify the effects of PM on the pasture intake, milk production, milk composition, and grazing behavior of strip- or rotational-grazing dairy cows, based on a meta-analysis of published research papers. A database was created that included experiments in which the effects of PM on pasture intake and milk production of dairy cows were studied. Papers were selected only if at least 2 PM were compared under similar experimental conditions, particularly the same pasture allowance (SPA). The final database included 15 papers with 27 PM comparisons. For analytical purposes, the database was subdivided into 3 subsets that varied according to the estimation height at which pasture allowance was determined; that is, where PM were compared at the SPA above ground level (SPA_0 subset), above 2 to 3 cm (SPA_3 subset), and above 4 to 5 cm (SPA_5 subset). Statistical analyses were conducted on the entire database (global analysis) and within each subset using linear model procedures. An interaction between PM and estimation height was found for pasture intake and milk production in the global analysis. On the basis of the predictive equations, pasture intake increased by 1.58 kg of dry matter/d per tonne increase in PM when PM were compared at SPA_0, was not affected by PM when PM were compared at SPA_3, and decreased by 0.65 kg of dry matter/d per tonne increase in PM when PM were compared at SPA_5. This is consistent with the effect of PM on milk production, which was positive and negative (1.04 and −0.79 kg/t of PM, respectively) when PM were compared at SPA_0 and SPA_5, respectively. Grazing time was only slightly affected by PM, irrespective of estimation height, because the effect of PM on pasture intake was mainly dependent on the variation in pasture intake rate. Pasture intake rate increased with increasing PM at SPA_0 but decreased with increasing PM at SPA_5. This meta-analysis clearly demonstrates that the effects of PM on pasture intake, milk production, and behavior of strip-grazing dairy cows depend largely on the height at which the PM and pasture allowance are measured. These results have methodological implications for future grazing research because it can be recommended that PM be compared at similar levels of pasture availability (i.e., at the same pasture allowance above 2 to 3 cm) to avoid possible misinterpretations of results. They also reveal the benefits of improving grazing management and intake prediction through modeling in pasture-based dairy systems.

Key words: dairy cow, pasture mass, estimation height, meta-analysis

INTRODUCTION

Grazing management is a key factor in determining the efficiency of pasture-based dairy systems. It is recognized as the main tool for controlling pasture utilization and per-cow production, and reaching the optimal balance between these factors is the main objective for dairy farms trying to achieve maximum profitability. A major issue is, however, the lack of control over feed quality and availability throughout the year (Dillon et al., 2005). Large variation in pasture growth rate between seasons along with different practices in grazing management (e.g., rotation length or fertilization level) result in significant variation in pregrazing pasture mass (**PM**). Pregrazing PM is, therefore, directly related to farming decisions, and an advanced knowledge of its effect on pasture intake and milk production may be useful in improving grazing management in pasture-based dairy systems.

The effects of pregrazing sward height (i.e., PM) have been extensively studied under continuously

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stocked management, in which pasture intake and milk production were shown to decline with decreasing sward height (Rook et al., 1994; Gibb et al., 1997). In very short swards, cows are unable to fully compensate for the reduction in pasture intake rate by extending grazing time, and the daily pasture intake is penalized (Hodgson, 1986). Indeed, short-term pasture intake rate decreases with decreasing PM because of the strong reduction in bite mass, which is only partially compensated for by the increase in biting rate (Hodgson, 1986; Ungar, 1996). In contrast, few such studies have been conducted under strip-grazing management, with Delagarde et al. (2001) being the first to review the effect of PM on pasture intake. Furthermore, no previous meta-analysis has investigated the effect of PM on pasture intake, nor has any review or meta-analysis studied the effect of PM on milk production or on the grazing behavior of strip-grazing dairy cows.

Under strip- or rotational-grazing management, intake and milk production are primarily affected by pasture allowance (**PA**), that is, the product of PM and daily offered area (Peyraud et al., 1996; Dalley et al., 1999; Maher et al., 2003). Under such grazing systems, the daily offered area is a limiting factor, and the effect of pregrazing PM is generally studied by comparing 2 or more PM at similar PA. However, the height above which PM and PA are expressed (i.e., estimation height) is variable and depends on grazing management practices. In New Zealand and Australia, PM and PA are normally estimated by cutting pastures manually with electric shears at ground level (Holmes et al., 1992; Wales et al., 1999). In European countries, such as France and Ireland, pasture is usually sampled by cutting strips with a motor scythe at 4 or 5 cm above ground level (Ribeiro Filho et al., 2003; Wims et al., 2010), but can also be sampled at ground level (Stakelum, 1986a; Peyraud et al., 1996) or at 2 or 3 cm above ground level (Stakelum and Dillon, 2004; Pérez-Prieto et al., 2011). Previous reviews (Baudracco et al., 2011; Delagarde et al., 2011b) demonstrated that the estimation height has a direct and mechanical effect on the relationship between pasture intake and PA, this being a consequence of pasture bulk density, which increases from the top to the bottom of the sward profile. The pasture intake/PA slope is lower, with an estimation height of 4 to 5 cm above ground level. Delagarde et al. (2001) suggested a similar effect of the estimation height on the relationship between pasture intake and PM. They proposed, based on a literature review, that pasture intake increases with increasing PM when PM are compared at the same PA (**SPA**) above ground level (**$\mathbf{SPA_0}$**), whereas pasture intake decreases with increasing PM when PM are compared at the SPA above 4 or 5 cm (**$\mathbf{SPA_5}$**). They also suggested that PM had no effect on pasture intake when PM are compared at the SPA above an intermediate height, namely, above 2 to 3 cm (**$\mathbf{SPA_3}$**). This hypothesis was then used as a basis for the GrazeIn model used to predict pasture intake by dairy cows (Delagarde et al., 2011a). The external validation of the GrazeIn model when using a large independent data set showed no relationship between the intake bias (predicted minus actual) and the pregrazing PM over a wide range of PM, suggesting the hypothesis was correct (Delagarde et al., 2011b). Recently, Pérez-Prieto et al. (2012) has also confirmed this hypothesis under experimental grazing conditions in which 2 PM were compared simultaneously at SPA_0, SPA_3, and SPA_5.

The objective of the present work was to perform a meta-analysis of the effect of pregrazing PM on pasture intake, milk production, milk composition, and grazing behavior of strip-grazing dairy cows. In particular, the study aimed to determine if the effect of PM was related to the estimation height at which PM and PA were measured. Predictive equations derived from this investigation will allow for a better understanding of the effects of PM, which will in turn be useful knowledge for modeling the intake and performance of dairy cows, and to improve grazing management in pasture-based dairy systems.

MATERIALS AND METHODS

Literature Search and Data Entry

A computerized literature search (Agricola, CAB Abstracts, and Web of Science) was conducted to identify papers in which the effects of pregrazing PM on the pasture intake or milk production of dairy cows were studied. The search was carried out using different combinations of the following key words: dairy cow, grazing, mass, herbage, pasture. Further papers were then selected by reviewing the reference lists in the publications resulting from the initial search. Papers were chosen if they met the following criteria: (1) included temperate regions and temperate sward species, (2) included lactating dairy cows under strip- or rotational-grazing management, (3) included a comparison of at least 2 PM under similar experimental conditions, particularly at the SPA. After discarding publications with duplicate data (i.e., results from the same experiment published several times), a starting database was constructed that included 19 papers and 48 PM comparisons. The database was conceptualized with rows representing treatments within an experiment and columns reporting treatment characteristics and least squares means of measured variables. Each paper was categorized by author name(s), year of pub-

lication, and country. Each PM comparison was allocated an individual code (study) and was characterized by grazing system, season, pasture type, experimental design, experimental duration, number of cows, preexperimental cow characteristics, estimation height, and the method used to estimate pasture intake. The cutting instrument used to measure pregrazing PM was also included as a characteristic for each PM comparison. The authors were contacted personally, whenever possible, to inquire about this information when it was not reported in their paper. In experiments in which the interaction between PM and another factor was studied (e.g., at 2 supplementation levels or 2 fertilization levels), PM comparisons conducted under similar experimental conditions were considered independent studies.

Data Filtering

Investigations solely reporting PM comparisons carried out with minimal concentrate (<1 kg of DM/d) and no forage supplementation were selected (n = 7, number of studies eliminated). Furthermore, studies including very high PM (i.e., >4.0 t of DM/ha above 5 cm or >7.0 t of DM/ha above ground level, approximately) or with very low pasture quality at high PM were rejected because of the risk of accumulated effects between PM and pasture quality (n = 7). Additionally, studies were excluded if the difference between PM treatments was less than 0.7 t of DM/ha (n = 4) or because of inconsistencies in pasture intake results regarding animal characteristics and milk production (n = 3).

Calculations

At least 2 of the following 3 parameters were needed to calculate the remaining parameters: PM, PA, and offered area (PA = PM × daily offered area). Data were standardized before quantitative and statistical analyses. Pregrazing PM and PA were expressed in tonnes of DM per hectare and kilogram of DM per cow per day, respectively. The database included papers in which PM and PA were estimated above ground level and at 2.5, 3, 4, 4.5, or 5 cm. For analytical purposes, the database was divided into 3 subsets: PM compared at SPA_0 (SPA_0 subset), PM compared at the SPA above 2.5 or 3 cm (SPA_3 subset), and PM compared at the SPA above 4, 4.5, or 5 cm (SPA_5 subset). In the SPA_3 subset, PM and PA above 2.5 cm were standardized and recalculated above 3 cm. In the SPA_5 subset, PM and PA above 4 and 4.5 cm were standardized and recalculated above 5 cm. This was done according to the following general equations calibrated from a large data set including pure perennial ryegrass and ryegrass/white clover pastures, reported in or modified from Delagarde et al. (2011a):

$$PM_0 = 1.06 \times PM_{2.5} + 1{,}452,$$

$$PM_0 = 1.13 \times PM_4 + 1{,}903,$$

$$PM_0 = 1.15 \times PM_{4.5} + 2{,}021,$$

$$PM_3 = 0.92 \times PM_0 - 1{,}499,$$

$$PM_5 = 0.85 \times PM_0 - 1{,}811,$$

where PM_0, $PM_{2.5}$, PM_3, PM_4, $PM_{4.5}$, and PM_5 are pregrazing PM above ground level and at 2.5, 3, 4, 4.5, and 5 cm, respectively.

For subsequent global analysis, the database was reorganized, creating a second database (slopes database). This was based on the within-experiment slopes of the relationship between PM and the dependent variables. In each PM comparison, slopes were calculated by dividing the difference between the values of the dependent variable in the highest and the lowest PM by the difference between the highest and the lowest PM (expressed as per-tonne increase in PM). This methodology enabled a comparison of the effect of PM between studies and, hence, between the estimation heights without any correction of absolute PM values.

Fat-corrected milk production (4% FCM) was calculated according to the method of INRA (2007). Daily average pasture intake rate (g of DM/min) was calculated by dividing pasture intake (kg of DM/d) by grazing time (min/d).

Statistical Analyses

Statistical analyses were conducted independently in the SPA_0, SPA_3, and SPA_5 subsets. The study effect was considered random and a structured variance-covariance matrix for the intercepts and slopes was included (random covariance not significant; St-Pierre, 2001). Data were analyzed using the following model (PROC MIXED; SAS Institute, 1999):

$$R_y = \text{a} + \text{study} + \text{b} \times \text{PM},$$

where R_y is the predicted variable y in response to the pregrazing change in PM, a is the overall intercept, study is the random effect of the study (PM comparison), and b is the overall linear regression coefficient. The overall quadratic regression coefficient was tested

but not included in the final analyses because it was not significant in all subsets ($P > 0.05$).

The overall intercepts, the overall regression linear coefficients, and standard deviations are reported for all data in which the regression from the mixed model was significant (i.e., $P < 0.10$). Observations adjusted for the study effect were calculated according to the method of St-Pierre (2001) by using the following equation: Y adjusted = Y predicted + residual. The Y predicted are the Y values on the regression line calculated with the mixed model.

In addition, a global analysis was performed that included data in the slopes database to test the fixed effect of the estimation height (i.e., PM compared at SPA_0, SPA_3, and SPA_5) on the dependent variable/PM slopes. Data were analyzed using the following model (PROC GLM; SAS Institute, 1999):

$$Y_{ijk} = \mu + \text{estimation height} + e_{ijk},$$

where Y_{ijk}, μ, estimation height, and e_{ijk} represent the analyzed variable, the overall mean, the fixed effect of the estimation height, and the residual standard error term, respectively. The linear and quadratic effects of the estimation height were tested by orthogonal contrasts. The least squares means and standard deviations are reported for all data in which the regression from the linear model was significant (i.e., $P < 0.10$).

RESULTS

Database Description

The final PM database was composed of 15 experiments taken from 15 papers published between 1986 and 2012, with 27 PM comparisons (23 between 2 PM and 4 between 3 PM; Table 1). The grazing system was solely strip-grazing (27), predominantly on perennial ryegrass swards (18) or mixed perennial ryegrass/white clover swards (9). Pasture intake was determined either by a sward-sampling technique (12), indirectly from fecal output and pasture digestibility (5), or by using the *n*-alkanes technique (9). The pasture intake methodology was, however, not reported in one paper. The studies were reported from Ireland, France, Australia, New Zealand, and the United Kingdom. The effect of PM was studied at SPA_0 (11; in Ireland, New Zealand, Australia, and France), at SPA_3 (3; in Ireland and France), and at SPA_5 (13; in the United Kingdom, Ireland, and France; Table 1). Motor-driven sheep-shearing handpieces, sheep shearers, or scissors were the instruments used to cut pastures to ground level, electric hand shears or a rotary mower was used to cut above 2.5 or 3 cm, and a motor scythe or an auto scythe was used to cut above 4 or 5 cm. All studies were carried out in the spring or summer, and the experimental design was either continuous (17), Latin square (5), or simple switchback (5). The number of cows in each PM comparison varied from 6 to 68, mainly according to the experimental design. The average low and high PM were 3.2 and 4.7 t of DM/ha in the SPA_0 subset, 2.1 and 4.0 t of DM/ha in the SPA_3 subset, and 1.7 and 3.2 t of DM/ha in the SPA_5 subset, respectively.

Cow characteristics were similar between subsets, with the variation in BW (505 to 559 kg), stage of lactation (84 to 145 DIM), milk production (19.8 to 24.7 kg/d), and pasture intake (14.7 to 16.2 kg of DM/d) being relatively low (Table 2). The mean durations of the experiments were 3, 8, and 9 wk in the SPA_0, SPA_3, and SPA_5 subsets, respectively. Pasture allowance averaged 31 kg of DM/d above ground level, 19 kg of DM/d above 3 cm, and 17 kg of DM/d above 5 cm in the SPA_0, SPA_3, and SPA_5 subsets, respectively. Pasture digestibility averaged 781 g/kg and was similar between subsets and between PM within each subset. Fewer results were available for milk production than for pasture intake, except in the SPA_5 subset, in which the amount of data for milk production was greater. Data collected on the grazing behavior were scarce, varying from 2 to 13 depending on the studied variable and subset (Table 2).

Effect of Pregrazing PM in the SPA_0 Subset

When PM were compared at SPA_0, pasture intake increased with increasing PM in all the PM comparisons of this subset, except one (Figure 1A). On the basis of the predictive equations, pasture intake increased linearly by 1.58 kg/t of PM ($P < 0.01$; Table 3), and milk production appeared to increase with increasing PM (+1.04 kg/t of PM; $P = 0.08$; Figure 2A). Grazing time was not affected by PM, and herbage intake rate increased by 4.83 g of DM/min per tonne of PM ($P < 0.01$).

Effect of Pregrazing PM in the SPA_3 Subset

The mixed model was significant only for pasture intake, grazing time, and pasture intake rate ($P < 0.10$; Table 3). On the basis of the predictive equations, PM had no effect on pasture intake ($P > 0.10$; Figure 1B). Grazing time tended to decrease (−22 min/t of PM; $P = 0.07$), whereas pasture intake rate tended to increase (+1.6 g of DM/min per tonne of PM; $P = 0.08$) with increasing PM.

Table 1. Summary of the 27 pasture mass (PM) comparisons included in the meta-analysis to determine the effect of pregrazing PM on pasture intake, milk production, and grazing behavior of strip-grazing dairy cows when PM were compared at the same pasture allowance (SPA) above ground level (SPA_0 subset), above 3 cm (SPA_3 subset), and above 5 cm (SPA_5 subset)

Reference	Country[1]	EH,[2] cm	Cutting instrument[3]	PM comp.[4]	Ss[5]	No. of cows[6]	Design[7]	Parity[8]	DIM[9]	PM,[10] t of DM/ha			Concentrate, kg of DM/d
										Lowest	Highest	Dif.	
SPA_0 subset													
Stakelum (1986a)	IE	0.0	MDSH	2	Spr.	40	CT	All	83	3.2	3.9	0.7	0.0
Stakelum (1986b)	IE	0.0	MDSH	2	Sum.	40	CT	Mult.	196	3.7	4.7	1.0	0.0
Holmes et al. (1992)	NZ	0.0	MDSH	1	Spr.	20	CT	NR	29	2.8	5.5	2.7	0.0
Wales et al. (1999)	AU	0.0	Sheep shearer	4	Spr.	48	CT	Mult.	36	3.1	4.9	1.8	0.0
Lee et al. (2008)	NZ	0.0	MDSH	1	Spr.	30	CT	Mult.	59	2.8	3.9	1.1	0.0
Pérez-Prieto et al. (2012)	FR	0.0	Scissors	1	Spr.	8	SB	All	147	3.5	5.4	1.9	0.0
SPA_3 subset													
Stakelum and Dillon (2004)	IE	3.0	Rotary mower	2	Spr.	12	LS	Mult.	91	2.2	3.7	1.5	0.0
Pérez-Prieto et al. (2012)	FR	2.5	EMS	1	Spr.	8	SB	All	147	2.0	4.2	2.2	0.0
SPA_5 subset													
Christie et al. (2000)	UK	4.0	UN	1	Spr.	36	CT	Mult.	129	2.5	3.5	1.0	0.0
Parga et al. (2002)	FR	5.0	Motor scythe	2	Spr.	12	LS	Mult.	186	1.3	3.8	2.5	0.2
Ribeiro Filho et al. (2003)	FR	5.0	Motor scythe	1	Spr.	6	LS	All	218	1.2	3.3	2.1	0.3
Delagarde et al. (2004)	FR	5.0	Motor scythe	2	Spr.	12	SB	Mult.	185	2.2	3.7	1.5	0.2
Stakelum and Dillon (2007)	IE	4.5	Motor scythe	1	Sum.	42	CT	NR	154	2.4	3.4	1.0	0.0
Curran et al. (2010)	IE	4.0	Auto scythe	2	Sum.	64	CT	All	58	1.5	2.8	1.3	0.0
Wims et al. (2010)	IE	4.0	Auto scythe	1	Spr.	46	CT	All	46	1.1	2.0	0.9	0.0
McEvoy et al. (2010)	IE	4.0	Auto scythe	2	Sum.	68	CT	All	118	1.7	2.8	1.1	0.0
Pérez-Prieto et al. (2012)	FR	5.0	Motor scythe	1	Spr.	8	SB	All	147	1.0	3.6	2.6	0.0

[1]Country codes as given in ISO 3166-1: IE = Ireland; NZ = New Zealand; AU = Australia; FR = France; UK = United Kingdom.

[2]EH = estimation height (i.e., height above which PM and pasture allowance were estimated).

[3]MDSH = motor-driven sheep-shearing handpiece; EMS = electric manual shears; UN = unknown.

[4]Number of PM comparisons considered from each paper.

[5]Ss = season; Spr. = spring; Sum. = summer.

[6]Number of cows used in the PM comparison(s) considered from each paper.

[7]Experimental design: CT = continuous; SB = switchback; LS = Latin square.

[8]Mult. = multiparous; Primi. = first calving; All = Mult. + Primi.; NR = not reported.

[9]DIM = DIM at the start of treatment.

[10]PM above ground level in the SPA_0 subset, above 3 cm in the SPA_3 subset, and above 5 cm in the SPA_5 subset; Dif. = within-experiment difference between the lowest and highest PM.

Table 2. Summary statistics of the studies included in the meta-analysis to determine the effect of pregrazing pasture mass (PM) on pasture intake, milk production, and grazing behavior of strip-grazing dairy cows when compared at the same pasture allowance (SPA) above ground level (SPA_0 subset), above 3 cm (SPA_3 subset), and above 5 cm (SPA_5 subset)[1]

	SPA_0 subset					SPA_3 subset					SPA_5 subset				
Item	n	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n	Mean	SD	Min	Max
Experiment length, wk	23	4	1.3	2	5	6	9	4.1	4	12	29	8	3.5	4	15
DIM at start of treatment	23	84	62.0	29	197	6	110	28.9	91	147	29	145	52.8	46	218
BW, kg	23	505	41.3	425	579	6	537	30.7	517	584	29	559	38.0	495	609
PM,[2] t of DM/ha	23	3.9	0.87	2.8	5.5	6	2.9	0.89	1.8	3.7	29	2.3	0.93	0.8	3.8
Pasture allowance,[3] kg of DM/d	23	31	15.6	15	70	6	19	4.0	14	22	29	17	5.7	11	31
Digestibility,[4] g/kg															
Low PM	11	752	50.5	700	850	3	810	38.7	765	832	9	797	34.2	763	855
High PM	11	765	50.3	700	871	3	794	21.4	769	806	9	769	45.7	711	829
Pasture intake, kg of DM/d	23	14.7	3.05	6.7	22.3	6	15.3	1.98	12.7	16.8	24	16.2	1.24	14.1	18.6
Milk production, kg/d	15	24.7	3.23	19.9	32.0	2	24.6	0.71	24.1	25.1	29	19.8	4.03	9.6	26.9
Milk fat concentration, g/kg	7	40.6	2.18	37.8	44.2	2	37.5	0.41	37.0	37.9	23	39.1	2.15	36.1	44.7
Milk protein concentration, g/kg	7	32.1	1.23	30.6	33.7	2	31.5	0.21	31.3	31.6	23	33.0	1.91	30.0	37.4
4% FCM production, kg/d	7	23.0	1.84	20.0	25.3	2	23.7	0.45	23.3	24.0	23	19.9	4.48	9.5	27.7
Milk fat production, g/d	7	924	74.1	800	1,021	2	921	10.8	913	928	23	788	183.0	377	1,130
Milk protein production, g/d	7	731	48.7	670	817	2	774	27.5	754	793	23	660	145.2	359	896
Grazing time, min/d	10	481	43.7	402	545	6	520	31.1	480	557	13	511	45.6	429	608
Ruminating time, min/d	10	422	26.7	387	477	2	414	61.2	370	457	8	471	46.2	380	530
Pasture intake rate, g of DM/min	10	29.6	7.60	16.2	44.8	6	29.4	3.62	24.0	34.0	8	31.5	2.89	27.3	36.4

[1]n = number of data; Min = minimum; Max = maximum.

[2]PM above ground level in the SPA_0 subset, above 3 cm in the SPA_3 subset, and above 5 cm in the SPA_5 subset.

[3]Pasture allowance above ground level in the SPA_0 subset, above 3 cm in the SPA_3 subset, and above 5 cm in the SPA_5 subset.

[4]Digestibility as given in the paper (i.e., in vitro or in vivo OM or DM digestibility).

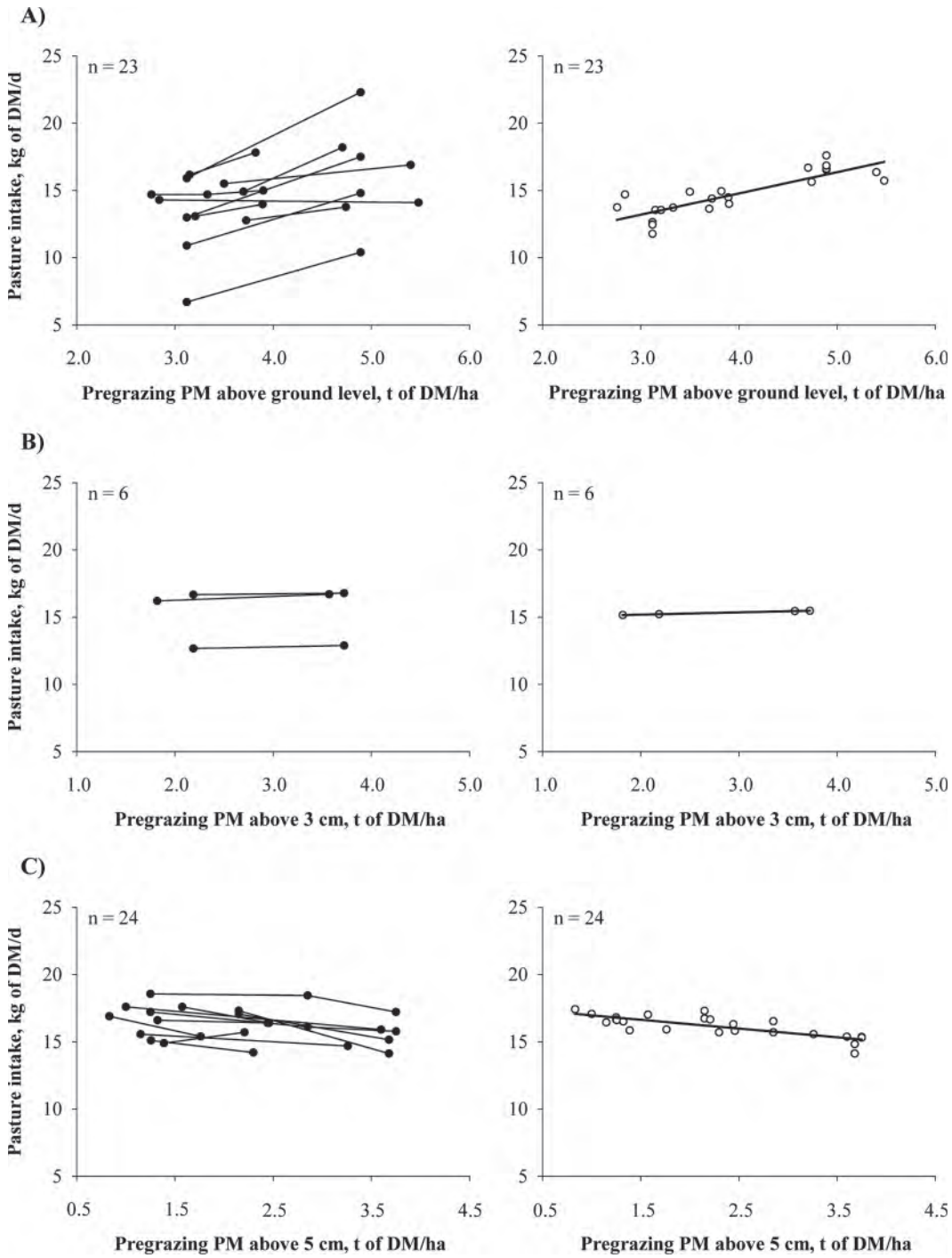

Figure 1. Effect of pregrazing pasture mass (PM) on pasture intake of strip-grazing dairy cows when compared at the same pasture allowance (SPA): A) above ground level (SPA_0 subset), B) above 3 cm (SPA_3 subset), and C) above 5 cm (SPA_5 subset). Plots on the left report raw data (●) from each study included in the meta-analysis (1 line = 1 PM comparison). Plots on the right report adjusted observations (○) and the mean regression line from the mixed model analysis if $P < 0.10$ (R_y = a + study + b × PM).

Effect of Pregrazing PM in the SPA_5 Subset

The mixed model was significant for pasture intake, milk production, and milk composition variables ($P <$ 0.10; Table 3). With the exception of one result, all the PM comparisons in this subset presented a negative effect of PM on pasture intake (Figure 1C). On the basis of the predictive equations, pasture intake decreased on

Table 3. Within-experiment relationship between pregrazing pasture mass (PM) and pasture intake, milk production, milk composition, and grazing behavior of strip-grazing dairy cows when compared at the same pasture allowance (SPA) above ground level (SPA_0 subset), above 3 cm (SPA_3 subset), and above 5 cm (SPA_5 subset)[1]

Item	No. of data	SD	a	b	*P*-value, PM effect
SPA_0 subset					
Pasture intake, kg of DM/d	23	1.22	8.5	1.58	0.002
Milk production, kg/d	15	1.37	20.7	1.04	0.074
Grazing time, min/d	10	14.7	493	−3.1	0.586
Pasture intake rate, g of DM/min	10	1.91	9.9	4.83	0.004
SPA_3 subset					
Pasture intake, kg of DM/d	6	0.01	14.8	0.17	0.116
Grazing time, min/d	6	4.5	583	−22.0	0.063
Pasture intake rate, g of DM/min	6	0.88	24.8	1.63	0.073
SPA_5 subset					
Pasture intake, kg of DM/d	24	0.64	17.6	−0.65	0.002
Milk production, kg/d	29	0.70	22.3	−1.09	0.003
Milk fat concentration, g/kg	23	1.41	37.0	0.88	0.080
Milk protein concentration, g/kg	23	0.37	33.3	−0.16	0.320
4% FCM production, kg/d	23	0.85	22.1	−1.04	0.018
Milk fat production, g/d	23	41.8	850	−32.7	0.064
Milk protein production, g/d	23	34.8	743	−41.1	0.002

[1]Equation: R_y = a + study + b × PM.

average by 0.65 kg/t of PM ($P < 0.01$). Production of milk, 4% FCM, and milk protein decreased by 1.09 kg/d ($P < 0.01$; Figure 2B), 1.04 kg/d ($P < 0.05$), and 41.1 g/d ($P < 0.01$) per tonne increase of PM, respectively. Milk fat production tended to decrease with increasing PM (−33 g/d per tonne of PM; $P = 0.07$; Table 3). Milk fat concentration tended to increase with increasing PM (+0.9 g/kg per tonne of PM; $P = 0.09$), and milk protein concentration was not affected by PM.

Global Analysis (Slopes Database)

Variation in pasture intake, milk production, and pasture intake rate with regard to pregrazing PM were affected by the estimation height (linear model: $P < 0.10$; Table 4). Pasture intake increased with increasing PM at SPA_0 (+1.7 kg of DM/d per tonne of PM), was not affected by PM at SPA_3, and decreased with increasing PM at SPA_5 (−0.8 kg of DM/d per tonne of PM). The pasture intake/PM slope was linearly affected by the estimation height ($P < 0.001$). Similarly, milk production increased by 1.23 kg/t of PM at SPA_0, did not vary at SPA_3, and decreased by 0.92 kg/t of PM at SPA_5 (linear effect of estimation height, $P < 0.01$). The effect of PM on pasture intake rate depended largely on the estimation height. Pasture intake rate increased greatly with increasing PM at SPA_0 (+5.1 g of DM/min per tonne of PM) but decreased with increasing PM at SPA_5 (−1.8 g of DM/min per tonne of PM). At SPA_3, pasture intake rate was not affected by PM. The effect of PM on grazing time was not affected by the estimation height.

DISCUSSION

The aim of the present work was to determine the quantitative effect of PM on pasture intake, milk production, milk composition, and grazing behavior of dairy cows under strip- or rotational-grazing management through an extensive literature review.

Effect of PM Depends Largely on the Estimation Height

According to the present meta-analysis, the effects of PM on pasture intake, milk production, and grazing behavior are directly related to the methodology used to estimate PM and thus PA. In studies in which PM were compared at SPA_0, pasture intake increased by 1.3 to 3.6 kg of DM/t of PM (Stakelum, 1986a; Wales et al., 1999). Conversely, the effect of PM on pasture intake was negative in the experiments in which PM were compared at SPA_5 (−0.4 to −0.6 kg of DM/t of PM; Parga et al., 2002; Ribeiro Filho et al., 2003). The fact that the pasture intake/PM slope, in absolute value, was greater when PM were compared at SPA_0 than at SPA_5 suggests that the effects of PM on pasture intake can be better highlighted at SPA_0 rather than at SPA_5. It is difficult to underline a variation in pasture intake if the difference is lower than 1 kg of DM/d between treatments. Consequently, a range of 1 t of DM/ha between 2 PM may be sufficient to find a significant effect of PM on pasture intake when compared at SPA_0, but probably not at SPA_5. According to the review by Delagarde et al. (2001) and the hypothesis

Table 4. Global analysis of the effect of pregrazing pasture mass (PM) on pasture intake, milk production, and grazing behavior of strip-grazing dairy cows when compared at the same pasture allowance (SPA) above different estimation heights (EH): above ground level (SPA_0), above 3 cm (SPA_3), and above 5 cm (SPA_5)

		PM				*P*-value, EH effect	
Slope	No. of data	SPA_0	SPA_3	SPA_5	SD	Linear	Quadratic
Pasture intake, kg of DM/d per tonne of PM	25	1.74	0.21	−0.81	0.983	<0.001	0.904
Milk production, kg/d per tonne of PM	21	1.23	0.06	−0.92	1.513	0.009	0.549
Pasture intake rate, g of DM/min per tonne of PM	12	5.12	0.95	−1.83	1.839	<0.001	0.466

of the GrazeIn model to predict pasture intake of dairy cows (Delagarde et al., 2011a), PM should have no effect on pasture intake when PM are compared at the SPA above an intermediate height (i.e., above 2 to 3 cm). Although few results were available (n = 6) in the literature, this hypothesis was confirmed in the present meta-analysis, in which pasture intake was not affected by PM when PM were compared at SPA_3.

These results were not related to the country or the method used to estimate pasture intake because the effect of PM on pasture intake was always related to the estimation height even within the same country. As an example, the positive effect of PM at SPA_0 has been observed in Ireland and Australia when using both the *n*-alkanes technique and the cutting technique for measuring pasture intake (Stakelum, 1986a,b; Wales

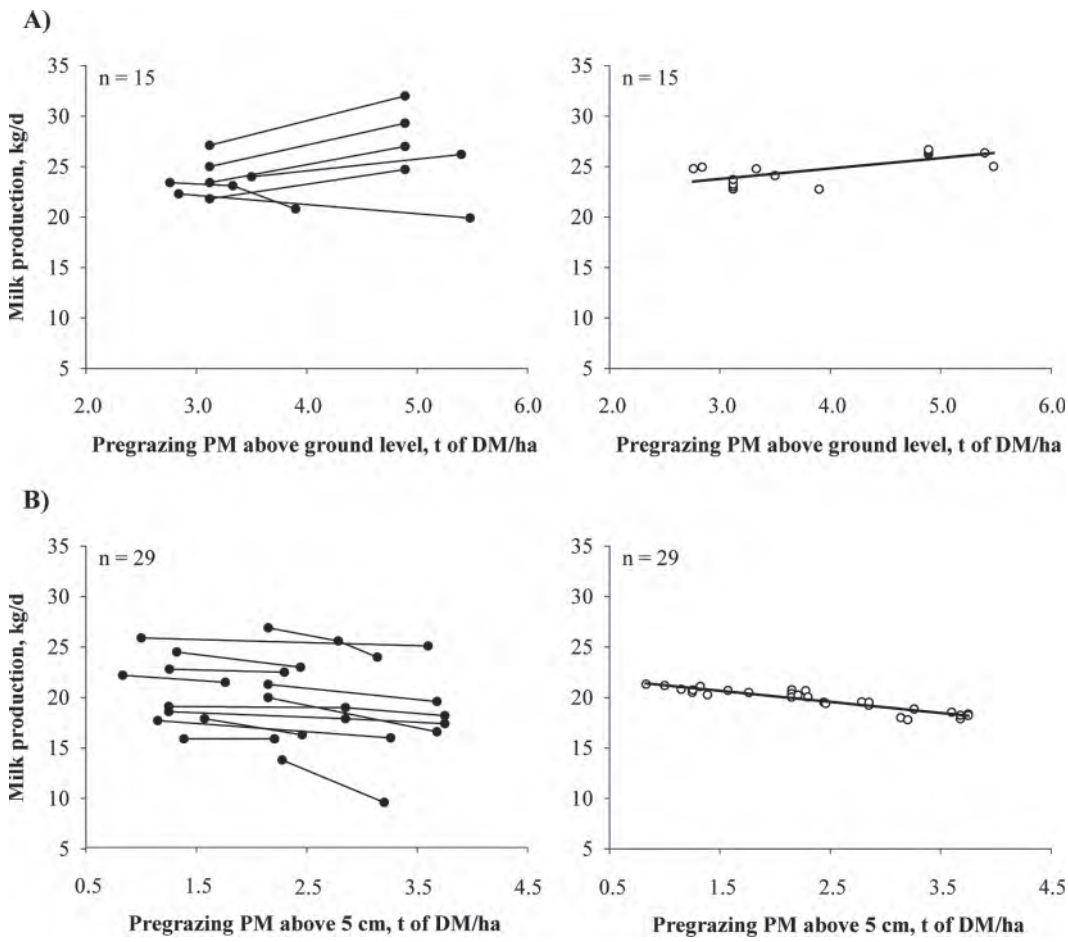

Figure 2. Effect of pregrazing pasture mass (PM) on milk production of strip-grazing dairy cows when compared at the same pasture allowance (SPA): A) above ground level (SPA_0 subset), and B) above 5 cm (SPA_5 subset). Plots on the left report raw data (●) from each study included in the meta-analysis (1 line = 1 PM comparison). Plots on the right report adjusted observations (○) and the mean regression line from the mixed model analysis if $P < 0.10$ (R_y = a + study + b × PM).

et al., 1999; Stakelum and Dillon, 2007). This is also clearly illustrated in the recent study by Pérez-Prieto et al. (2012), in which 2 different PM were compared simultaneously at SPA_0, SPA_3, and SPA_5. This trial was conducted in France, and pasture intake was estimated using the *n*-alkanes technique. The effect of PM on pasture intake was positive (0.74 kg of DM/t of PM), nil, and negative (−0.65 kg of DM/t of PM) when PM were compared at SPA_0, SPA_3, and SPA_5, respectively.

The global analysis in the present investigation demonstrated the interaction between PM and estimation height, with the slope between pasture intake and PM decreasing linearly from +1.74 to −0.81 kg of DM/t of PM when the estimation height increased from 0 to 5 cm. This was consistent with milk production, which also increased, was unaltered, and decreased when PM were compared at SPA_0, SPA_3, and SPA_5, respectively. According to the conceptual approach of Delagarde et al. (2011a), this interaction may be because, under a wide range of PM, both the PA above ground level and the PA above 5 cm are unreliable estimators of the pasture actually available to cows. It is known that cows are unable to reach ground level while grazing, even under very severe grazing conditions, and evidence exists to suggest that they can graze below 5 cm to a postgrazing plate meter sward height of 2 to 3 cm (Stockdale, 1996; Lee et al., 2007; Pérez-Prieto et al., 2011). Assuming that pasture below 2 to 3 cm is ungrazable and that pasture between 2 to 3 cm and 5 cm is grazable, it can be assumed that PA above 2 to 3 cm would be a better estimator of the pasture actually available to cows. In the experiment by Pérez-Prieto et al. (2012), PM above 2.5 cm was directly measured and enabled the calculation of PA above 2.5 cm. When PM were compared at SPA_0, the ungrazable stratum (below 2 to 3 cm) was quantitatively greater at low PM rather than at high PM because of the larger offered area at low PM. Pasture availability was, therefore, lower at low PM rather than at high PM (17 vs. 24 kg of DM/d of PA above 2.5 cm), explaining the positive effect of PM on pasture intake at SPA_0. In contrast, when PM were compared at SPA_5, the grazable stratum (between 2 to 3 and 5 cm) was quantitatively greater at low PM rather than at high PM because of the larger area offered at low PM. Pasture availability was greater at low PM rather than at high PM (31 vs. 20 kg of DM of PA above 2.5 cm), explaining the negative effect of PM. Pasture intake was not affected by PM when pasture availability was similar between low and high PM, that is, when PM were compared at SPA_3 (23 vs. 23 kg of DM/d of PA above 2.5 cm). Graphical and conceptual representations of this approach can be found in Delagarde et al. (2011a) and Pérez-Prieto et al. (2012). In perennial ryegrass-based pastures, it can thus be recommended to measure PA above 2 to 3 cm to accurately estimate the amount of pasture actually available to cows over a wide range of PM.

Behavioral Adaptation to PM Variation

When PM changes do not affect pasture quality, as in the studies included in the present meta-analysis, the effect of PM on intake is expected to be related to nonnutritional intake regulation (i.e., behavioral adaptation to pasture availability; Poppi et al., 1987). According to the predictive equations, the effect of PM on pasture intake mainly appeared to be related to variation in pasture intake rate, with grazing time not being affected (SPA_0 subset) or being only slightly affected (SPA_3 subset) by PM. The SPA_5 subset had no significant equation for grazing time because of inconsistent results on the effect of PM.

In the SPA_0 subset, the large increase in pasture intake rate with increasing PM (5 g of DM/min per tonne of PM) was consistent with results previously reported for dairy cows continuously grazing on temperate grasslands at different sward surface heights (Rook et al., 1994; Gibb et al., 1997). In such grazing systems, grazing time is generally increased as a compensatory response to the reduction in pasture intake rate with decreasing PM. Indeed, cows can graze for more than 700 min/d to compensate for the low pasture intake rate caused by very short swards (4 to 6 cm, plate meter; Hodgson, 1986; Rook et al., 1994). Under continuously stocked management, pasture availability in terms of kilograms of DM per day per cow is theoretically unlimited because of the large area offered and low instantaneous stocking rate. Furthermore, sward height is not reduced throughout the day, and cows consume only the upper leafy strata (Gibb et al., 1997). Grazing conditions are thus relatively easy throughout the day, allowing cows to extend their grazing time (Rook et al., 1994; Prache and Peyraud, 1997; Parga et al., 2000). In contrast, under strip- or rotational-grazing management, a grazing time of more than 600 min/d has seldom been recorded (Bargo et al., 2002; Kennedy et al., 2007; Stakelum and Dillon, 2007), and grazing time generally averages between 450 and 550 min/d. Indeed, under such conditions, cows are forced to graze lower into the sward profile because of the restricted area offered daily, leading to more difficult grazing conditions and a lower pasture intake rate at night compared with the morning (Barrett et al., 2001). In the process of grazing down a sward shorter and shorter, the intake becomes increasingly predominated by pseudostem and dead material, probably reducing the motivation of cows to

keep on grazing and thus limiting the grazing time. Conversely, under continuous-grazing management, pasture intake rate may even increase throughout the day because of increased pasture DM and soluble carbohydrate concentrations (Gibb et al., 1998; Gregorini, 2012). The meta-analysis presented here thus seems to demonstrate different behavioral adaptations in cows on a daily basis according to changes in PM between rotational and continuously stocked grazing management systems.

According to the global analysis, the decrease in pasture intake with increasing PM in the SPA_5 subset was related, at least partially, to the reduction in pasture intake rate (−2 g of DM/min per tonne of PM). No significant equation was obtained for grazing time because results noted in the literature were inconsistent, with both positive and negative effects of PM on grazing time being reported. The reduction in pasture intake rate with increasing PM appears to contradict the numerous results obtained in short-term experiments, which all showed a positive and strong relationship between pasture intake rate and PM on a minute to hour basis (Hodgson, 1986; Rook et al., 1994; Gibb et al., 1997). On a daily basis, PM has also been reported to affect pasture intake rate positively when PM are compared at SPA_0 (SPA_0 subset; Wales et al., 1999; Pérez-Prieto et al., 2012). This clearly indicates that, under strip- or rotational-grazing management, average daily grazing behavior cannot be predicted from a single description of pregrazing pasture characteristics (e.g., PM or sward height). Pregrazing pasture descriptions do not include grazing conditions for the entire grazing-down process, given that grazing conditions during the second half of this process are far more difficult than those in the first hours of grazing (Barrett et al., 2001). Average daily pasture intake rate should be considered as an integrated variable, which takes into account pasture availability from early morning until late at night. When a new strip of fresh pasture is available in the morning, it can be hypothesized that immediate pasture intake rate is greater at high PM rather than at low PM because of the greater bite mass (Barrett et al., 2001). At the end of the day, cows at high PM are forced to graze the stem and pseudostem layer, previously identified as a major source of resistance for pasture intake (Wade, 1991). Indeed, in studies by Ribeiro Filho et al. (2003) and Pérez-Prieto et al. (2012), sheath defoliation depth was 3 to 4 times greater, and sheath defoliation volume (defoliation depth × offered area) was almost twice as great at high PM rather than at low PM when compared with similar PA above 5 cm. This suggests that the time spent grazing sheath strata is much longer at high PM than at low PM, probably reducing pasture intake rate despite the higher postgrazing sward height. During the second half of the day, a much lower instantaneous pasture intake rate can thus be expected at high PM rather than at low PM, to achieve an average pasture intake rate lower at high PM than at low PM.

When PM are compared at SPA_3 (SPA_3 subset), the absence of any effect of PM on pasture intake was related to low variation in both grazing time and pasture intake rate. According to the predictive equations, a compensatory process appears to take place in which the apparent reduction in pasture intake rate with decreasing PM is compensated for by a tendency to increase the grazing time. Consequently, it can be suggested that grazing conditions between PM are almost similar when PM are compared at SPA_3, with the difference between low and high PM being compensated for by the difference between areas offered daily in each PM. This is clearly observed in the experiment by Pérez-Prieto et al. (2012), in which postgrazing extended lamina height, a variable recognized as an accurate estimator of grazing severity (Wade, 1991), was similar between low and high PM only when compared at SPA_3.

Practical Implications

The present work has established, statistically, that the effects of PM on pasture intake, milk production, and grazing behavior depend on the cutting height above which PM and PA are estimated. The results of this meta-analysis thus corroborate the only other experiment carried out to demonstrate this interaction between PM and the estimation height (Pérez-Prieto et al., 2012). The primary practical implication resulting from this investigation is that part of the variation in pasture intake, attributed to changes in PM, is due to the methodological choice for conducting the experiment. In this respect, any treatment affecting pregrazing PM directly or indirectly, such as sward type or fertilization level, can affect intake, depending on the methodology used for estimating PM and PA. The final effect of a treatment on pasture intake will, therefore, be a combination of the treatment effect per se and of the indirect effect of PM resulting from different methodological approaches. To avoid such confusion and possible misinterpretations of results, PM should be compared at similar levels of pasture availability (i.e., at the SPA above 2 to 3 cm). The choice of the researcher to work at SPA_0 or SPA_5 is, therefore, decisive for the experimental outcome. Consequently, under strip- or rotational-grazing management, it may be strongly recommended that treatments with different PM be compared at similar levels of pasture availability (i.e., SPA_3).

According to our results, PM had no effect on pasture intake and milk production when PM were compared at SPA_3. However, the 3 studies included in this subset were short-term experiments (approximately 1 to 3 mo), and it would be interesting to confirm these results in the long term, specifically, during the entire grazing season or over several successive grazing seasons. When a grazing season is considered, pregrazing PM is mainly controlled by the grazing rotation length. Experiments studying the effects of grazing rotation length are, however, scarce and date back more than 20 to 30 yr (McFeely et al., 1975; Leaver, 1985). In the experiment by McFeely et al. (1975) and according to the comprehensive review by Leaver (1985), grazing rotation length does not appear to affect the performance of dairy cows under strip- or rotational-grazing management, corroborating results obtained in the present meta-analysis.

Models to predict pasture intake by grazing dairy cows were reviewed by Delagarde and O'Donovan (2005). In their review, the effect of PM was not clearly established in most of the existing models. The equations reported in the present meta-analysis may, therefore, be useful in determining the effect of PM in models in which the effects of PM and PA are considered either above ground level or at 2, 3, 4, or 5 cm above ground level. For example, the GrazeIn model (Delagarde et al., 2011a) includes no effect of PM on pasture intake because PM and PA are standardized above 2 cm. The Diet Check model (Heard et al., 2004) considers a positive effect of PM or compressed sward height on pasture intake because PM is measured at ground level. These 2 modeling options are consistent with the height at which PM is considered in their respective models, and both are consistent with the results of this meta-analysis. A predictive model based on PM and PA determined above 5 cm should necessarily include a negative effect of PM on pasture intake.

The meta-analysis presented here focused on dairy cows grazing on temperate pastures. The transferability of these results to experiments using other types of ruminants (e.g., young cattle, sheep, or goats) or other types of pastures (e.g., tropical grasslands) is unknown. It is probable that the threshold height of 2 to 3 cm is not adequate to determine pasture availability for animals being able to graze lower into the sward profile. Similarly, the morphological characteristics of the pasture probably play an important role in determining the height at which pasture availability should be defined, with swards richer in stem and pseudostem being more difficult to graze.

CONCLUSIONS

The present meta-analysis has facilitated the understanding of the contradictory results reported previously on the effect of PM on pasture intake, milk production, and grazing behavior of dairy cows when PM were compared at similar PA under strip- or rotational-grazing management. The positive, absence of, or negative effect of PM found in the literature can now be clearly attributed to the methodology used to compare PM, namely, the height at which PM and PA are measured. Pasture intake and milk production responses to PM in relation to the estimation height vary primarily because of pasture intake rate because grazing time displayed only low variation with regard to PM irrespective of the estimation height. This study has important implications for future grazing research and the interpretation of results for modeling the intake, performance, and behavior of grazing dairy cows and for improving grazing management in pasture-based dairy systems. Both PA above ground level and PA above 5 cm were unreliable estimators of the pasture actually available to cows under a wide range of PM. To avoid possible misinterpretations of results, it is thus recommended that ryegrass-based pastures be compared with different PM at the SPA above 2 to 3 cm, which is the best estimate of the actual available pasture.

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