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

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ABSTRACT

Daily pasture allowance (PA) is defined as the product of pregrazing pasture mass and offered area, and is the major grazing management factor determining pasture utilization per unit area and daily performance of grazing dairy cows. The objective of the present study was to perform a meta-analysis reviewing the effect of PA on pasture intake, milk production, milk composition, and grazing behavior of dairy cows. Experiments studying the effect of PA on pasture intake or milk production, which eventually included milk composition or grazing behavior data, or both, were selected to create a database. Papers were selected only if at least 2 PA were compared under the same experimental conditions, particularly the same pasture mass (i.e., where PA levels were only obtained through changes in daily offered area). The final database included 97 PA comparisons reported in 56 papers. For analytical purposes, the database was subdivided into 3 subsets that varied according to the estimation height (EH) at which PA was determined; that is, PA above ground level (PA_0 subset), PA above 2.5 to 3.5 cm (PA_3 subset), and PA above 4 to 5 cm (PA_5 subset). Statistical analyses were conducted independently on the PA_0, PA_3, and PA_5 subsets and on the whole database (global analysis) by using linear and nonlinear mixed-model procedures. The curves, either exponential, quadratic, or linear, describing the effects of PA on pasture intake, milk production, or grazing behavior of dairy cows are conceptually similar, whatever the EH. The equations describing these curves are, however, specific for each EH. Accordingly, from typical low to high PA, the increase in pasture intake (0.13 vs. 0.21 vs. 0.28 kg/kg of PA), milk production (0.11 vs. 0.17 vs. 0.24 kg/kg of PA), and milk solids production (0.008 vs. 0.010 vs. 0.013 kg/kg of PA) per kilogram of increase in PA was lower for PA_0 than for PA_3, and for PA_3 than for PA_5. Grazing time increased from low to medium PA and did not vary from medium to high PA. Pasture intake rate seemed to increase from low to medium PA because of greater bite mass, whereas it increased from medium to high PA because of greater biting rate. The present meta-analysis demonstrated that the general relationship between PA and any dependent variable is quite strong and independent of EH. This suggests no specific relationship for some parts of the world or methodology approach, with a high portability of the global equations calculated here. These results are useful for improving grazing management and modeling on pasture-based dairy systems.
Key words: dairy cow, pasture allowance, estimation height, meta-analysis

INTRODUCTION

The profitability and sustainability of pasture-based dairy systems depend on efficient use of available grassland coupled with reasonable milk production per cow (Dillon et al., 2005). Under strip- or rotational-grazing management, even with high-quality pastures, pasture utilization per unit area and pasture intake per cow are major factors determining milk production of grazing dairy cows, both being primarily controlled by pasture allowance (**PA**; in kg of DM/cow per day; Poppi et al., 1987; Dalley et al., 1999). Daily PA is defined as the product of pregrazing pasture mass and offered area per animal. On most dairy farms, the offered area is usually easily regulated by electric fences, which are a major grazing management tool for controlling herd grazing conditions on a day-to-day scale. Reducing the offered area (i.e., decreasing PA at a constant pregrazing pasture mass) increases pasture utilization and milk production per hectare and penalizes pasture intake and milk production per cow (Baudracco et al., 2010; Peyraud and Delagarde, 2013). Similar results are observed under rotational grazing management, with grazing conditions being controlled by residence time within a paddock instead of offered area (Hoden et al., 1986). The antagonist effect of PA on per-cow and per-hectare production has been reported in medium- (Peyraud et al., 1996; Pérez-Prieto et al., 2011a) and

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long-term studies, where the concept of PA is usually replaced by stocking rate (cows/ha; Dillon et al., 1995; Macdonald et al., 2008; McCarthy et al., 2011). Pasture allowance is, therefore, directly related to farmer decisions and advanced knowledge of the effect of PA on pasture intake and milk production may be useful in improving grazing management.

Determining the optimum PA is not an easy task because it depends on, and varies with, pasture and animal characteristics. Consequently, many studies investigating the effect of PA have been conducted over the last decades. The height at which PA is estimated (i.e., estimation height, **EH**) is, however, variable and depends on grazing management practices and on the machinery used to cut the pasture. In New Zealand and Australia, pasture allowance is usually estimated by cutting at ground level (Stockdale, 1993; Suksombat et al., 1994; Wales et al., 1999). In European countries such as France and Ireland, the cutting height is variable, and PA may be estimated above ground level (**PA_0**; Stakelum, 1986a; Ribeiro Filho et al., 2005), above 2.5 to 3.5 cm (**PA_3**; Maher et al., 2003; Pérez-Prieto et al., 2011a), or above 4 to 5 cm (**PA_5**; Pérez-Ramírez et al., 2009; McEvoy et al., 2010). Due to the high bulk density in the deeper strata of a sward canopy (Delagarde et al., 2000b; Pérez-Prieto et al., 2013), the absolute value of pasture mass in a given pasture greatly varies according to the EH, as well as the estimated value of PA for a given offered area (Delagarde et al., 2011; Pérez-Prieto and Delagarde, 2012). As an example, a daily PA of 20 to 25 kg of DM/d is considered as low when measured at ground level (Wales et al., 1999) and high when measured above 5 cm (Delagarde et al., 2011). Consequently, the effect of increasing 1 kg/d of PA on pasture intake is lower for PA_0 (0.10 to 0.20 kg/kg of PA_0; Peyraud et al., 1996; Wales et al., 1999) than for PA_5 (0.20 to 0.30 kg/kg of PA_5; Parga et al., 2002; Curran et al., 2010). Estimation height should, therefore, be considered when reviewing the effect of PA, to avoid misinterpretations or erroneous equations obtained from the confounded analysis of experiments carried out with PA estimated at different EH (Pérez-Prieto and Delagarde, 2012).

The effect of PA on pasture intake of dairy cows has already been reviewed in several papers over the last 20 yr. Most of these reviews only considered studies with PA_0 (Mayne, 1991; Stockdale, 2000), or PA standardized above ground level (Delagarde et al., 2001) or above 2 cm (Delagarde et al., 2011) when considering papers differing in EH. In the review by Bargo et al. (2003), the effect of PA on intake was calculated without any discrimination between studies, merging results from the mixed analysis of PA_0 to PA_5. Baudracco et al. (2010) on the other hand, reviewed the effect of PA on intake by working independently with PA_0 and with PA above a given height (3, 4, or 5 cm). Those authors clearly showed that the relationship between PA and intake largely depends on the EH, even though they grouped PA above 3, 4, and 5 cm without any correction. Previous grazing research has, however, demonstrated significant differences in the results obtained with EH of 3 and 5 cm (Pérez-Prieto and Delagarde, 2012; Pérez-Prieto et al., 2013).

According to all these reviews, several equations describe the effect of PA_0, but few or none describe the effect of PA above 2, 3, 4, or 5 cm (Delagarde and O'Donovan, 2005). Moreover, no meta-analyses exist describing the effect of PA on milk production and milk composition, or any reviews or meta-analyses studying the effect of PA on grazing behavior parameters at the daily scale. The objective of the present work was to perform a meta-analysis reviewing the effect of PA on pasture intake, milk production, milk composition, and grazing behavior of dairy cows. The meta-analysis was carried out assuming a major role of the EH on PA effect, different equations being calculated for each EH. The results of the present study will provide valuable knowledge to improve grazing management in pasture-based dairy systems. Moreover, predictive equations derived from this research will be useful for modeling the intake and performance of dairy cows at grazing.

MATERIALS AND METHODS

Literature Search and Data Entry

A computerized literature search [Agricola (http://agricola.nal.usda.gov/), CAB Abstracts (http://www.cabi.org/Default.aspx?site=170&page=1016&pid=125), and Web of Science (http://thomsonreuters.com/web-of-science/)] was conducted to identify papers where the effect of PA on pasture intake or milk production in lactating dairy cows was studied. These papers eventually also studied the effect of PA on milk composition or grazing behavior, or both, as additional measurements. The search was carried out using the following key words in different combinations: dairy cow, grazing, allowance, herbage, and pasture. More papers were then identified by reviewing the reference list in the publications resulting from the search. Papers were selected if they met the following criteria: (1) temperate regions and temperate sward species, (2) lactating dairy cows under strip- or rotational-grazing management, (3) a comparison of at least 2 PA under the same experimental conditions, particularly same pasture mass (i.e., where PA levels were only obtained through changes in daily offered area). After discarding publications with duplicated data (i.e., results from the same experiment published several times), a starting database was obtained. The initial database included 61 papers with 140 PA comparisons. It was conceptualized with rows representing treatments within experiments and columns reporting treatment characteristics and least squares means of measured variables. Each paper was identified by author(s), year of publication, and country. Each PA comparison was allocated an individual code (study) and was characterized by grazing system, season, sward type, experimental design, experimental length, number of cows, preexperimental cow characteristics, EH, and the method to estimate pasture intake. In experiments where PA was studied in interaction with another factor (e.g., at 2 supplementation levels or 2 nitrogen fertilization levels), PA comparisons conducted under similar experimental conditions were considered independent studies.

Data Filtering

Studies solely reporting PA comparisons carried out with unrestricted daily access time at pasture (>18 h/d; n = 3, number of studies eliminated) and minimal supplementation level were selected (≤1 kg of DM concentrate/d and no forage supplementation; n = 38, number of studies eliminated). Data corresponding to PA below 15 kg of DM/d above ground level were not included in the meta-analysis because these highly severe grazing treatments seem to not be applicable to lactating dairy cows, methodological difficulties in pasture mass and PA measurements being suspected (n = 2).

Calculations

At least 2 of the 3 following variables were needed to calculate the remaining variable: pasture mass, PA, and offered area (PA = pasture mass × daily offered area). Data were standardized before quantitative and statistical analyses. Pregrazing pasture mass and PA were expressed in tonnes of DM per hectare and kilograms of DM per cow per day, respectively. The filtered database included papers where pasture mass and PA were estimated above ground level, 2.5, 3, 3.5, 4, or 5 cm. For analytical purposes, the database was divided into 3 subsets: PA estimated above ground level (PA_0 subset), PA estimated above 2.5 to 3.5 cm (PA_3 subset), and PA estimated above 4 to 5 cm (PA_5 subset). In the PA_3 subset, pasture mass and PA originally reported above 2.5 and 3.5 cm were standardized and recalculated above 3 cm. In the PA_5 subset, pasture mass and PA above 4 cm were standardized and recalculated above 5 cm. For subsequent global database analyses with fixed EH, pregrazing pasture mass and PA were standardized and recalculated above ground level, 3, and 5 cm in all the studies included in the meta-analysis. This was done according to the following equations calibrated from pure perennial ryegrass (*Lolium perenne* L.) and perennial ryegrass-white clover (*Trifolium repens* L.) pastures, reported in or developed from Delagarde et al. (2011):

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

$$PM_0 = 1.08 \times PM_3 + 1{,}621,$$

$$PM_0 = 1.10 \times PM_{3.5} + 1{,}759,$$

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

$$PM_0 = 1.17 \times PM_5 + 2{,}142,$$

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

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

where PM_0, $PM_{2.5}$, PM_3, $PM_{3.5}$, PM_4, and PM_5 are pregrazing pasture mass (kg of DM/ha) above ground level, 2.5, 3, 3.5, 4, and 5 cm, respectively.

To facilitate the description of results and comparisons between the 3 subsets, 3 theoretical PA classes were established: low, medium, and high. These 3 PA classes are reported for each EH in Table 1. According to previous studies (Dalley et al., 1999; Wales et al., 1999), low, medium, and high PA_0 correspond to 20, 40, and 60 kg of DM/d, respectively. The corresponding theoretical levels for PA_3 and PA_5 were recalculated from the daily offered area (fixed for each PA) and the average pasture mass above ground level, 3, and 5 cm of the whole database (i.e., 4.6, 2.7, and 2.1 t of DM/ha, respectively). Accordingly, the average pasture mass in the database is 1.9 t of DM/ha between 0 and 3 cm, 0.6 t of DM/ha between 3 and 5 cm, and 2.5 t of DM/ha between 0 and 5 cm (Delagarde et al., 2011).

Fat-corrected milk production (4% FCM) was calculated according to the Institut National de la Recherche Agronomique (INRA) method (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) for all studies where both variables were available.

Statistical Analyses

Statistical analyses were conducted independently on the PA_0, PA_3, and PA_5 subsets and on the whole database (global analysis with fixed EH) by using the

Table 1. Theoretical values for low, medium, and high pasture allowances (PA) established from the literature above ground level[1]

Item	Low PA	Medium PA	High PA
PA_0, kg of DM/d	20	40	60
PA_3, kg of DM/d	12	24	36
PA_5, kg of DM/d	9	18	27
Offered area, m^2/d	44	87	131

[1]Equivalences between PA above ground level (PA_0), above 3 cm (PA_3), and above 5 cm (PA_5) are calculated from the offered area and the average pregrazing pasture mass above ground level, above 3 cm, and above 5 cm in the database (4.6, 2.7, and 2.1 t of DM/ha, respectively), recalculated when necessary according to the equations of pasture vertical distribution in Delagarde et al. (2011).

same models. Pasture intake and production of milk, milk solids, milk fat, and milk protein are recognized for presenting an exponential relation with PA, increasing at a declining rate to a maximum with increasing PA (Stockdale, 2000; Delagarde et al., 2001, 2011). Accordingly, these variables were analyzed by running a nonlinear mixed model. The model was conditioned to a normal (Gaussian) distribution and the study effect was considered random, specifying that it follows a normal distribution with mean 0 and 1 variance. The model was forced to pass through the origin, assuming that intake and production are 0 when no pasture is on offer. Data were analyzed by using the following model (PROC NLMIXED; SAS Institute, 2008):

$$R_y = a \times (1 - \exp^{(-b \times \text{PA})}) + \text{study},$$

where R_y is the predicted variable y in response to PA change, a is the overall intercept, b is the overall exponential coefficient, and study is the random effect of the study.

Grazing behavior, milk fat concentration, and milk protein concentration were analyzed by running a linear mixed model. The study effect was considered random and a structured variance-covariance matrix for the intercepts and slopes was included in the model, except when the random covariance was significant ($P < 0.05$) and an unstructured variance-covariance matrix was used (St-Pierre, 2001). Data were analyzed using the following model (PROC MIXED; SAS Institute, 2008):

$$R_y = a + \text{study} + b \times \text{PA} + c \times \text{PA}^2,$$

where R_y is the predicted variable y in response to PA change, a is the overall intercept, study is the random effect of the study, b is the overall regression linear coefficient, and c is the overall regression quadratic coefficient. This latter was tested for each variable and was not included in the final model if $P > 0.05$.

An additional global analysis was run on the whole database to determine, within the same relationship, the effects of both PA and EH. The model included the PA as originally estimated in each paper (i.e., above ground level, 2.5, 3, 3.5, 4, or 5 cm) and the fixed effect of EH. This was carried out by replacing the overall exponential, linear, or quadratic coefficient in the mixed models presented above by a linear fixed effect of EH (PROC NLMIXED; SAS Institute, 2008):

$$R_y = a \times (1 - \exp^{[-(b + c \times \text{EH}) \times \text{PA}]}) + \text{study}$$

and (PROC MIXED; SAS Institute, 2008)

$$R_y = a + \text{study} + (b + c \times \text{EH}) \times \text{PA} + (d + e \times \text{EH}) \times \text{PA}^2,$$

where d and e are, respectively, the overall intercept and overall linear regression coefficient of the linear effect of EH on the PA^2 variable.

The quadratic regression coefficient of EH was tested but not included in the final analysis because it was not significant ($P > 0.05$). The overall intercept; the overall regression linear, quadratic, or exponential coefficients; and the standard deviation are reported for all variables where the mixed models were significant ($P < 0.10$). Adjusted observations for the study effect were calculated according to St-Pierre (2001), by using the following equation: Y adjusted = Y predicted + residual, where Y predicted are the Y values on the regression line calculated with the mixed models.

RESULTS

Database Description

The final database included 97 PA comparisons reported in 56 papers published between 1966 and 2011 (Table 2). Grazing method was strip (84) or rotational grazing (13), including grass-based swards (69), mixed legume/grass swards (21), or legume-based swards (7). Pasture intake was determined by a sward-sampling technique (35), indirectly from fecal output and pasture digestibility (33), with the *n*-alkanes technique (24), or by an unreported method (5). Experimental design was either Latin square or switchback (37), or complete randomized design (60). The studies were from Argentina, Australia, Brazil, Finland, France, Ireland, Korea, the Netherlands, New Zealand, the United Kingdom, or the United States (Table 2). Most of the experiments were conducted in the spring and summer, or summer only. Pregrazing pasture mass and PA were estimated above ground level (47), above an intermediate height of 2.5 to 3.5 cm (11), or above 4 or 5 cm (39). Pregrazing pasture mass recalculated above ground level, 3 cm, and 5 cm averaged 4.6, 2.7, and 2.1 t of DM/ha, respectively.

In the PA_0 subset, the mean experiment lasted 6 wk and the average pregrazing pasture mass was 4.4 t of DM/ha (Table 3). The lowest and highest PA_0 averaged 21 and 43 kg of DM/d, respectively. In the PA_3 subset, the mean experiment lasted 9 wk and was conducted with an average pregrazing pasture mass above 3 cm of 2.5 t of DM/ha. Daily PA_3 averaged 18 and 27 kg of DM/d for the lowest and the highest values, respectively. In the PA_5 subset, the experiments lasted 9 wk, on average, and the pregrazing pasture mass above 5 cm was 2.4 t of DM/ha. The lowest and the highest PA_5 averaged 13 and 20 kg of DM/d, respectively. The actual average pasture digestibility was approximately 8% lower in the PA_0 subset than in the 2 other subsets, probably due to the lower sampling height. The known vertical distribution of digestibility in a sward profile (Delagarde et al., 2000b) and the 10% difference between the digestibility of pasture above ground level and that selected from a pasture with a postgrazing pasture height close to 5 cm (Stockdale et al., 2001) suggest similar average pasture quality between subsets. Average pasture intake (14.8 kg of DM/d) and milk production (18.9 kg/d) were similar between subsets (<1.2 kg/d of difference). Data available for milk composition and grazing behavior were lower than for pasture intake and milk production (Table 3).

Effect of PA in the PA_0 Subset

Based on the predictive equations and according to the PA classes described in Table 1, pasture intake (0.21 vs. 0.07 kg/kg of PA_0) and milk production (0.19 vs. 0.05 kg/kg of PA_0) increased more from low to medium PA_0 than from medium to high PA_0 (exponential effect, $P < 0.001$; Table 4 and Figure 1A). Production of 4% FCM, milk solids, milk fat, and milk protein per kilogram of PA_0 also increased at a declining rate with increasing PA_0. Concentrations of milk fat (−0.08 g/kg per kilogram of PA_0) and milk protein (0.07 g/kg per kilogram of PA_0) varied from low to medium PA_0, and were almost unaffected by PA_0 between medium and high PA levels. Grazing time increased by 3.0 and 0.9 min/d per kilogram of PA_0 from low to medium and from medium to high PA_0, respectively. Grazing time decreased from high to very high PA_0 (−1.2 min/d per kilogram of PA_0; quadratic effect, $P < 0.01$). Ruminating time did not vary according to PA_0, and pasture intake rate increased linearly by 0.29 g of DM/min per kilogram of PA_0 ($P < 0.001$).

Effect of PA in the PA_3 Subset

Pasture intake increased by 0.28 and 0.08 kg/kg of PA_3 from low to medium and from medium to high PA_3, respectively (exponential effect, $P < 0.001$; Table 4 and Figure 1B). On the basis of the predictive equations, production of milk, 4% FCM, milk solids, milk fat, and milk protein were not exponentially affected by PA_3. Milk fat concentration decreased more from low to medium than from medium to high PA_3 (−0.17 vs. −0.06 g/kg per kilogram of PA_3; quadratic effect, $P <$ 0.05). Milk protein concentration was not affected by PA_3. Data for grazing behavior were scarce in the PA_3 subset and the mixed model was significant only for pasture intake rate, which tended to linearly increase with increasing PA_3 ($P = 0.10$).

Effect of PA in the PA_5 Subset

Pasture intake (0.40 vs. 0.12 kg/kg of PA_5), milk production (0.35 vs. 0.07 kg/kg of PA_5), and 4% FCM production (0.30 vs. 0.05 kg/kg of PA_5) increased more from low to medium than from medium to high PA_5 (exponential effect; $P < 0.001$; Table 4 and Figure 1C). Production of milk solids, milk fat, and milk protein also increased at a declining rate with increasing PA_5 (exponential effect; $P < 0.001$). The effect of PA_5 on milk fat and milk protein concentrations was linear ($P < 0.001$), with milk fat concentration decreasing and milk protein concentration increasing with increasing PA_5 (−0.15 and 0.08 g/kg per kilogram of PA_5, respectively). Grazing time decreased from low to medium PA_5 and increased from medium to high PA_5 (−6 and 4 min/d per kilogram of PA_5, respectively; quadratic effect, $P < 0.05$). Ruminating time tended to increase linearly with increasing PA_5 ($P = 0.09$). The pasture intake rate increased by 0.62 g of DM/min per kilogram of PA_5 from low to medium PA_5 and was almost unaffected between medium and high PA levels (quadratic effect, $P < 0.05$). According to the predictive equations, PA_5 did not affect biting rate. Bite mass increased by 14 mg of DM/kg of PA_5 from low to medium PA_5 and did not vary between medium and high PA levels (quadratic effect, $P < 0.05$).

Global Analysis

Equations describing the exponential effect of PA on pasture intake, milk production, or milk solids production may be compared within each subset (Table 4) or considering the whole database (Table 5). In both cases, the equations differed mainly by the curvilinearity of the relationship (b parameter). This made the curves

Table 2. Summary of the 56 papers included in the meta-analysis to determine the effect of pasture allowance (PA) on pasture intake, milk production, milk composition, and grazing behavior of grazing dairy cows according to the estimation height (EH): ground level (PA_0 subset); 2.5, 3.0, or 3.5 cm (PA_3 subset); and 4.0 or 5.0 cm (PA_5 subset)

Reference	Country[1]	EH, cm	PA comp[2]	Season[3]	Parity[4]	DIM[5]	PA,[6] kg of DM/d Lowest	PA,[6] kg of DM/d Highest	Conc.,[7] kg of DM/d
PA_0 subset									
Combellas and Hodgson (1979)	UK	0.0	2	Sp./Su.	All	47 in all	15	43	0.0
Le Du et al. (1979)	UK	0.0	2	Sp./Su.	Mult.	14 in all	26	36	0.0
Bryant (1980)	NZ	0.0	3	Sp./Su.	NR	31/94/189	26	54	0.0
Glassey et al. (1980)	NZ	0.0	1	Sp.	NR	46	33	53	0.0
King and Stockdale (1984)	AU	0.0	2	Au.	All	210 in all	20	40	0.0
Stockdale and Trigg (1985)	AU	0.0	1	Au.	Mult.	225	15	26	0.0
Stakelum (1986a)	IE	0.0	1	Au.	Mult.	205	18	25	0.0
Stakelum (1986b)	IE	0.0	2	Sp.	All	79/86	15	23	0.0
Stakelum (1986c)	IE	0.0	2	Su.	Mult.	195/197	16	24	0.0
Mayne et al. (1987)	UK	0.0	1	Su.	Mult.	140	23	39	0.0
Grainger and Mathews (1989)	AU	0.0	1	Sp.	Mult.	21	17	33	0.0
Peyraud et al. (1989)	FR	0.0	1	Sp.	All	180	19	26	0.0
Stockdale (1992)	AU	0.0	3	Wi./Sp.	NR	59/16/23	15	62	0.0
Stockdale (1993)	AU	0.0	1	Sp.	NR	39	17	41	0.0
Suksombat et al. (1994)	NZ	0.0	1	Au.	All	48	20	43	0.0
Peyraud et al. (1996)	FR	0.0	2	Sp.	All	140 in all	21	51	0.7
Stockdale (1996)	AU	0.0	1	Au.	All	213	19	39	0.0
Robaina et al. (1998)	AU	0.0	1	Su.	NR	195	19	39	0.0
Wales et al. (1998)	AU	0.0	3	Au./Su.	All	215/197/207	15	70	0.0
Dalley et al. (1999)	AU	0.0	1	Sp.	NR	41	20	70	0.5
Wales et al. (1999)	AU	0.0	3	Sp./Su.	Mult.	36/36/126	20	70	0.0
Auldist et al. (2000)	NZ	0.0	2	Sp./Su.	Mult.	60/180	18	50	0.0
Dalley et al. (2001)	AU	0.0	1	Sp.	Mult.	39	40	65	0.0
Kim et al. (2001)	KR	0.0	1	Sp.	Mult.	NR	20	45	1.0
Wales et al. (2001)	AU	0.0	1	Sp.	Mult.	49	19	37	0.0
Bargo et al. (2002)	US	0.0	1	Sp./Au.	Mult.	101	27	49	0.8
Ribeiro Filho et al. (2005)	FR	0.0	2	Su.	Mult.	105 in all	21	36	0.2
Williams et al. (2005)	AU	0.0	2	Sp.	Mult.	44 in all	15	46	0.0
Ribeiro Filho et al. (2009)	BR	0.0	1	Sp.	All	129	24	37	0.0
Stockdale et al. (2011)	AU	0.0	1	Sp.	Mult.	78	20	40	1.0
PA_3 subset									
Mayne et al. (1987)	UK	2.5	1	Sp.	Mult.	79	27	56	0.0
Kuusela and Khalili (2002)	FI	3.0	1	Su.	NR	148	18	24	0.0
Virkajärvi et al. (2002)	FI	3.0	3	Su.	Mult.	141 in all	18	27	0.0
Maher et al. (2003)	IE	3.5	1	Sp./Su.	Mult.	50	16	24	0.0
Stakelum and Dillon (2004)	IE	3.0	2	Sp.	Mult.	91 in all	14	22	0.0
Stakelum et al. (2007)	IE	3.5	2	Sp.	All/Mult.	71/219	17	23	0.0
Pérez-Prieto et al. (2011b)	FR	2.5	1	Au.	Mult.	230	18	31	0.0
PA_5 subset									
Greenhalgh et al. (1966)	UK	4.0	1	Sp.	Mult.	70	11	25	0.0
Greenhalgh et al. (1967)	UK	4.0	3	Su.	Mult.	89/125/147	11	20	0.0
Meijs and Hoekstra (1984)	NL	4.0	2	Sp./Su.	Mult.	46/61	16	25	0.9
Hoden et al. (1991)	FR	5.0	1	Sp./Su.	All	51	14	19	1.0
Comerón et al. (1995)	AR	4.0	1	NR	NR	145	10	30	0.0
O'Brien et al. (1997)	IE	4.0	1	Sp./Su.	NR	66	16	24	0.0
Peyraud et al. (1998)	FR	5.0	1	Sp.	All	179	12	18	0.3
Delagarde et al. (2000a)	FR	5.0	1	Au.	NR	280	12	24	0.3
Parga et al. (2000)	FR	5.0	2	Sp.	All	177 in all	12	18	0.4
Delaby et al. (2001)	FR	5.0	3	Sp.	All	182/174/175	12	21	0.0
Crawford and Mayne (2002)	UK	4.0	2	Su.	Primi.	105/111	15	30	1.0
Parga et al. (2002)	FR	5.0	3	Sp.	Mult.	186 in all	12	18	0.2
Delagarde et al. (2004)	FR	5.0	2	Sp.	Mult.	185 in all	13	22	0.2
Kennedy et al. (2007a)	IE	4.0	4	Sp.	All	69 in all	17	31	0.0
Kennedy et al. (2007b)	IE	4.0	1	Sp.	All	14	13	19	0.0
Burke et al. (2008)	IE	4.0	1	Sp.	All	140	15	20	0.0
McEvoy et al. (2008)	IE	4.0	1	Sp.	All	18	13	17	0.0
Pérez-Ramírez et al. (2009)	FR	5.0	1	Sp.	NR	211	13	24	0.2
Curran et al. (2010)	IE	4.0	4	Sp./Su.	All	58/161	15	20	0.0

Continued

Table 2 (Continued). Summary of the 56 papers included in the meta-analysis to determine the effect of pasture allowance (PA) on pasture intake, milk production, milk composition, and grazing behavior of grazing dairy cows according to the estimation height (EH): ground level (PA_0 subset); 2.5, 3.0, or 3.5 cm (PA_3 subset); and 4.0 or 5.0 cm (PA_5 subset)

Reference	Country[1]	EH, cm	PA comp[2]	Season[3]	Parity[4]	DIM[5]	PA,[6] kg of DM/d		Conc.,[7] kg of DM/d
							Lowest	Highest	
McEvoy et al. (2010)	IE	4.0	4	Sp./Su.	All	57/148	16	20	0.0

[1]UK = United Kingdom; NZ = New Zealand; AU = Australia; IE = Ireland; FR = France; KR = Korea; US = United States; BR = Brazil; FI = Finland; NL = the Netherlands; AR = Argentina.

[2]Number of PA comparisons (comp) considered within each paper.

[3]Sp. = spring; Su. = summer; Au. = autumn; Wi. = winter; NR = not reported.

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

[5]Days in milk at the start of treatment application in each PA comparison.

[6]Lowest and highest PA above the respective EH.

[7]Concentrate (Conc.) level.

very similar, whatever the EH, when corresponding values of PA_0, PA_3, and PA_5 were considered in the same axis (Figure 2). This, combined with the fact that most data came from studies where PA was originally estimated above ground level, resulted in the decision to run a global analysis at ground level, PA_0 being recalculated when PA was not originally reported above ground level. An additional global analysis was then run to determine, besides the effect of PA, the effect of EH. This global approach was, however, run only for variables with a large number of data (i.e., pasture intake, milk production, milk solids production, and milk concentrations of fat and protein), which ensured the robustness of the equations.

Global Analysis of the Effect of PA_0. On the basis of the predictive equations and according to the PA classes defined in Table 1, pasture intake increased by 0.19 and 0.06 kg/kg of PA_0 from low to medium and from medium to high PA, respectively (Table 5; Figure 3). The increase in milk production (0.19 vs. 0.04 kg/kg of PA_0) and milk solids production (0.013 vs. 0.003 kg/kg of PA_0) was greater from low to medium than from medium to high PA. Milk fat concentration decreased (−0.08 g/kg per kilogram of PA_0) and milk protein concentration increased (0.02 g/kg per kilogram of PA_0) from low to medium PA, and both did not vary from medium to high PA (quadratic effect, $P < 0.01$; Figure 4). Grazing time increased by 2.2 and 0.9 min/d per kilogram of PA_0 from low to medium and from medium to high PA, respectively (quadratic effect, $P < 0.05$; Figure 5). Ruminating time was not affected by PA. Pasture intake rate increased linearly by 0.24 g of DM/min per kilogram of PA_0 ($P < 0.001$). Raw data for biting rate and bite mass were scarce. The relationship between PA and behavior at the bite level seems unclear (Figure 5). Based on the predictive equations, biting rate did not vary from low to medium PA and increased from medium to high PA (0.2 bites/min per kilogram of PA_0; quadratic effect, $P < 0.05$). Bite mass increased by 4.5 mg of DM/kg of PA_0 from low to medium PA and did not vary from medium to high PA (quadratic effect, $P < 0.05$).

Effect of PA According to EH. Pasture intake and production of milk, 4% FCM, milk solids, milk fat, and milk protein were affected by both PA ($P < 0.001$) and EH ($P < 0.001$; Table 6). From low to high PA, the increase in pasture intake per kilogram of PA increase was lower with an EH above ground level than above 3 cm or 5 cm (0.13 vs. 0.21 vs. 0.28 kg/kg of PA). From low to high PA, milk production (0.11 vs. 0.17 vs. 0.24 kg/kg of PA) and milk solids production (0.008 vs. 0.010 vs. 0.013 kg/kg of PA) increased more per kilogram of increase in PA_0 than PA_3 and PA_5. Production of milk fat and milk protein increased less per kilogram of increase in PA with an EH above ground level than above 3 cm or 5 cm (linear effect, $P < 0.001$). The effects of both PA and EH were significant for milk protein concentration ($P < 0.01$; $Ry = 29.4 + (0.115 + 0.026 \times EH) \times PA + (-0.00095 - 0.00064 \times EH) \times PA^2$; SD = 0.557). The model was not significant for milk fat concentration ($P > 0.10$).

DISCUSSION

The aim of this work was to determine the quantitative effect of PA on pasture intake, milk production, milk composition, and grazing behavior of dairy cows through literature review and meta-analysis. Pasture allowance has been one of the most extensively studied factors in grazing research, with many studies and reviews available. This is the first meta-analysis studying the effect of PA according to the EH, including intake, milk production, and grazing behavior.

Table 3. Summary statistics of the studies included in the meta-analysis to determine the effect of pasture allowance (PA) above ground level (PA_0 subset), above 3 cm (PA_3 subset), and above 5 cm (PA_5 subset) on pasture intake, milk production, milk composition, and grazing behavior of grazing dairy cows[1]

	PA_0 subset					PA_3 subset					PA_5 subset					
Item	n	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n	Mean	SD	Min	Max	Mean
Experiment length, wk	125	6	4.4	2	24	29	9	4.4	4	17	87	9	5.1	3	24	8
DIM at treatment start	122	108	73.8	14	225	29	126	56.2	50	230	87	122	63.4	14	280	115
BW, kg	117	507	59.4	374	631	27	541	18.4	517	563	72	546	44.7	461	630	524
PM,[2] t of DM/ha	125	4.4	1.27	2.2	7.3	29	2.5	0.69	1.5	4.1	87	2.4	0.81	1.1	4.2	—
PA,[3] kg of DM/d																
Lowest	47	21	6.7	15	53	11	18	2.8	14	24	39	13	2.5	9	22	—
Highest	47	43	13.7	22	70	11	27	9.4	14	53	39	20	3.7	13	28	—
Digestibility,[4] g/kg	108	728	61.7	587	830	29	781	69.3	617	858	73	792	55.9	627	874	758
Pasture intake, kg of DM/d	123	14.1	3.31	6.6	24.0	27	15.2	1.72	11.6	17.2	81	15.2	2.06	9.0	19.5	14.6
Milk production, kg/d	101	18.5	6.23	7.3	32.0	16	18.9	4.59	10.1	25.9	87	19.2	4.10	9.9	27.8	18.9
4% FCM production, kg/d	104	18.1	5.74	7.8	30.0	16	19.0	4.55	10.6	26.0	70	19.7	3.52	11.6	27.0	18.8
Milk solids production, kg/d	87	1.30	0.387	0.60	2.11	16	1.40	0.344	0.78	1.93	70	1.42	0.254	0.86	1.98	1.36
Milk fat production, kg/d	93	0.74	0.226	0.33	1.20	16	0.76	0.183	0.44	1.04	70	0.78	0.131	0.50	1.06	0.76
Milk protein production, kg/d	87	0.56	0.168	0.27	0.94	16	0.64	0.161	0.34	0.89	70	0.64	0.127	0.36	0.92	0.60
Milk fat concentration, g/kg	93	41.8	4.47	33.1	55.4	16	40.4	2.61	36.1	43.9	70	39.8	2.67	36.1	49.6	40.9
Milk protein concentration, g/kg	87	31.8	2.56	27.3	38.3	16	33.8	2.12	31.4	37.8	70	32.4	2.12	28.4	37.2	32.2
Grazing time, min/d	35	480	59.7	378	626	6	531	27.1	480	557	25	542	49.3	454	627	508
Ruminating time, min/d	33	419	75.5	210	522	2	388	7.8	382	393	19	469	42.7	390	532	436
Pasture intake rate, g of DM/min	35	29.7	5.63	16.2	44.8	6	26.3	3.62	21.9	31.0	25	28.4	3.70	21.4	36.4	28.9
Biting rate, bites/min	4	61	5.5	56	66	—	—	—	—	—	23	56	6.5	47	67	57
Bite mass, mg of DM	4	501	63.4	439	585	—	—	—	—	—	23	514	99.0	334	713	512

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

[2]Pasture mass above ground level in the PA_0 subset, above 3 cm in the PA_3 subset, and above 5 cm in the PA_5 subset.

[3]PA above ground level in the PA_0 subset, above 3 cm in the PA_3 subset, and above 5 cm in the PA_5 subset.

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

Table 4. Effect of pasture allowance (PA) above ground level (PA_0 subset), above 3 cm (PA_3 subset), and above 5 cm (PA_5 subset) on pasture intake, milk production, 4% FCM production, milk solids production, milk composition, and grazing behavior of grazing dairy cows

Item	Eq.[1]	No. of data	SD	Parameter[2] a	b	c	Significance PA	PA^2
PA_0 subset								
Pasture intake, kg of DM/d	Exp.[3]	123	1.77	18.1	0.053		***	
Milk production, kg/d	Exp.	101	2.91	21.2	0.071		***	
4% FCM production, kg/d	Exp.	104	2.82	20.2	0.081		***	
Milk solids production, kg/d	Exp.	87	0.180	1.47	0.075		***	
Milk fat production, kg/d	Exp.	93	0.109	0.82	0.081		***	
Milk protein production, kg/d	Exp.	87	0.076	0.66	0.064		***	
Milk fat concentration, g/kg	Quad.[4]	93	1.22	45.7	−0.22	0.0024	***	**
Milk protein concentration, g/kg	Quad.	87	0.49	28.7	0.14	−0.0012	***	***
Grazing time, min/d	Quad.	35	16.9	346	6.11	−0.052	***	**
Ruminating time, min/d	Lin.[5]	33	16.2	404	−0.10		NS	
Pasture intake rate, g of DM/min	Lin.	35	1.36	17.8	0.29		***	
PA_3 subset								
Pasture intake, kg of DM/d	Exp.	27	0.90	16.9	0.107		***	
Milk production, kg/d	Exp.	16	2.41	19.7	0.138		NS	
4% FCM production, kg/d	Exp.	16	2.38	19.4	0.159		NS	
Milk solids production, kg/d	Exp.	16	0.179	1.43	0.160		NS	
Milk fat production, kg/d	Exp.	16	0.095	0.77	0.181		NS	
Milk protein production, kg/d	Exp.	16	0.085	0.66	0.140		NS	
Milk fat concentration, g/kg	Quad.	16	0.54	45.9	−0.34	0.0046	*	*
Milk protein concentration, g/kg	Lin.	16	0.31	33.0	0.03		NS	
Pasture intake rate, g of DM/min	Lin.	6	1.07	18.0	0.44		†	
PA_5 subset								
Pasture intake, kg of DM/d	Exp.	81	1.16	17.5	0.136		***	
Milk production, kg/d	Exp.	87	2.22	20.6	0.185		***	
4% FCM production, kg/d	Exp.	70	1.98	20.6	0.207		***	
Milk solids production, kg/d	Exp.	70	0.142	1.50	0.191		***	
Milk fat production, kg/d	Exp.	70	0.075	0.81	0.218		***	
Milk protein production, kg/d	Exp.	70	0.071	0.69	0.165		***	
Milk fat concentration, g/kg	Lin.	70	1.00	42.2	−0.15		***	
Milk protein concentration, g/kg	Lin.	70	0.66	31.1	0.08		***	
Grazing time, min/d	Quad.	25	25.0	728	−20.85	0.549	*	*
Ruminating time, min/d	Lin.	19	18.1	434	2.03		†	
Pasture intake rate, g of DM/min	Quad.	25	1.18	13.1	1.43	−0.030	*	*
Biting rate, bites/min	Lin.	23	1.3	54	0.09		NS	
Bite mass, mg of DM	Quad.	23	24.4	162	34.54	−0.779	**	*

[1]Equation.

[2]a = overall intercept or overall asymptote; b = overall regression linear coefficient or overall exponential coefficient; c = overall regression quadratic coefficient.

[3]Exp. = exponential equation; $R_y = a \times (1 - \exp^{(-b \times \text{PA})}) + \text{study}$, where R_y is the predicted variable y in response to PA change and study is the random effect of the study.

[4]Quad. = quadratic equation; $R_y = a + \text{study} + b \times \text{PA} + c \times \text{PA}^2$.

[5]Lin. = linear equation; $R_y = a + \text{study} + b \times \text{PA}$.

†$P < 0.1$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

Effect of PA on Intake According to EH

Previous reviews have already reported a lower increase in pasture intake per kilogram of DM increase of PA when estimated above ground level rather than above 5 cm (Delagarde et al., 2001) or than above 3, 4, or 5 cm (Baudracco et al., 2010). This was confirmed in the present meta-analysis, where the average increase in pasture intake from low to high PA was 0.13, 0.21, and 0.25 kg/kg of PA_0, PA_3, and PA_5, respectively. This meta-analysis describes the exponential effect of PA, whatever the EH, offering global relationships applicable in a wide range of grazing management and methodological approaches. The variation in pasture intake:PA ratio according to EH is directly related to the amount of pasture considered in the calculation. For a given area, PA_0 is always greater than PA above a given height. This is primarily related to the consideration of more or less pasture from the sward profile (i.e., cutting upper or lower) but also to the vertical distribution of the pasture canopy. The fact that sward bulk density is much greater in the lower than in the upper strata (Delagarde et al., 2000b; Pérez-Prieto et al., 2013) amplifies PA differences. Accordingly, the difference between low and high PA is numerically greater for PA_0 than for PA_3, and for PA_3 than for PA_5. This

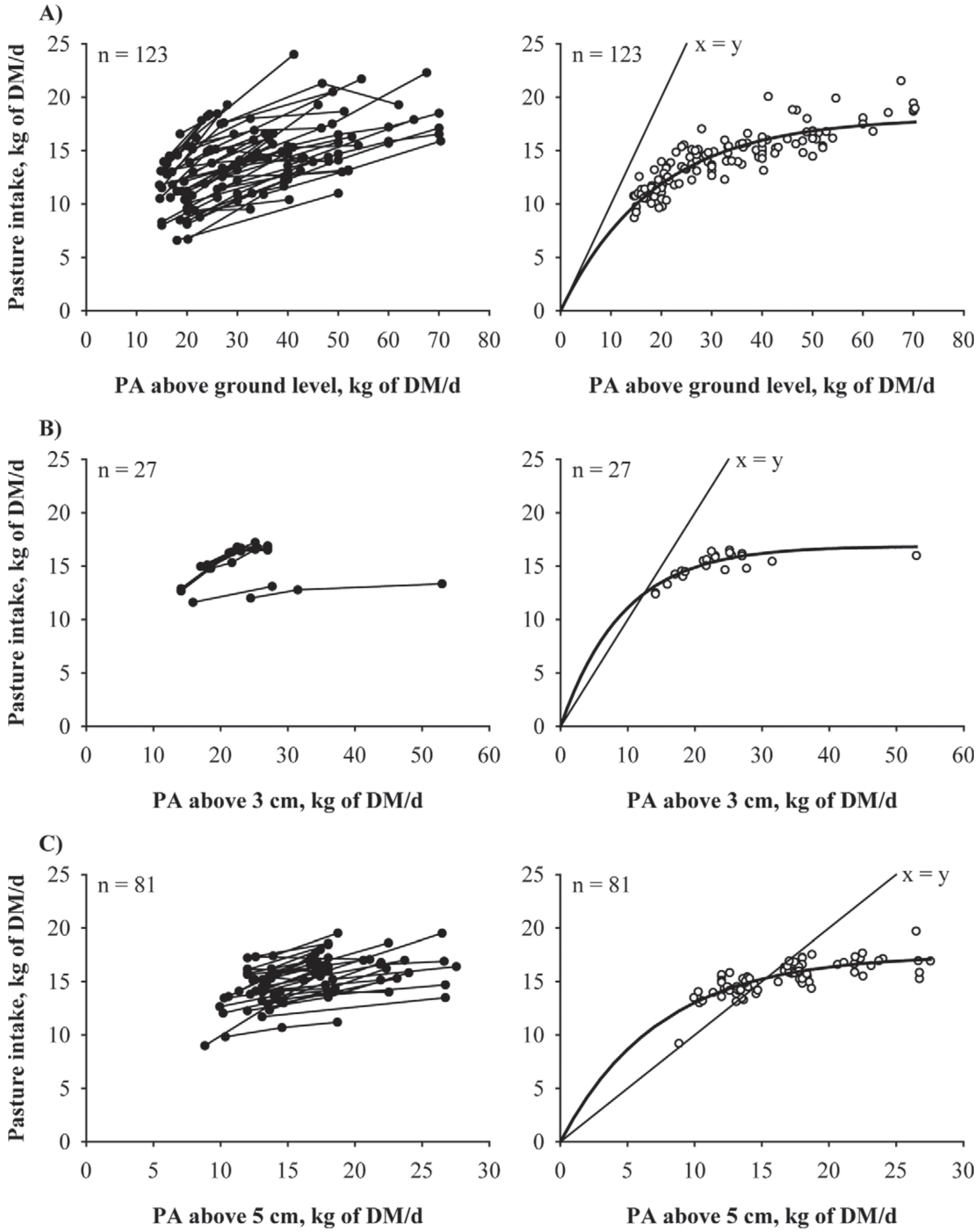

Figure 1. Effect of pasture allowance (PA): (A) above ground level (PA_0 subset), (B) above 3 cm (PA_3 subset), and (C) above 5 cm (PA_5 subset) on pasture intake of grazing dairy cows. Plots on the left report raw data (●) from each study included in the meta-analysis (1 line = 1 PA comparison). Plots on the right report adjusted observations (○) and the mean regression line from the mixed model analysis if $P < 0.10$. The equations are reported in Table 4 [$R_y = a \times (1 - \exp^{(-b \times \mathrm{PA})})$ + study, where R_y is the predicted variable y in response to PA change, a is the overall asymptote, b is the overall exponential coefficient, and study is the random effect of the study].

was clearly observed in the present study, where equivalences between PA with different EH were calculated. High PA is 40, 24, and 18 kg of DM/d greater than low PA when estimated above ground level, above 3 cm, and above 5 cm, respectively. The pasture intake:PA ratio is, therefore, lower for PA_0 than for PA_3 or PA_5 because of the numerically greater divisor in kilograms of DM per day between low and high PA.

According to the present meta-analysis, the general relationship between PA and intake, or between PA and any other dependent variable, is quite strong and independent of the methodology used to estimate PA

Table 5. Global analysis of the effect of pasture allowance (PA) above ground level (PA_0), above 3 cm (PA_3), and above 5 cm (PA_5), recalculated when not originally reported at the corresponding estimation height according to the equations in Delagarde et al. (2011), on pasture intake, milk production, and milk solids production, and of the effect of PA_0 on 4% FCM production, milk fat production, milk protein production, and grazing behavior in grazing dairy cows

Item	Eq.[1]	No. of data	SD	Parameter[2] *a*	*b*	*c*	Significance PA	PA^2
Pasture intake, kg of DM/d								
PA_0	Exp.[3]	231	1.53	17.8	0.057		***	
PA_3	Exp.	231	1.48	18.0	0.098		***	
PA_5	Exp.	231	1.74	17.7	0.142		***	
Milk production, kg/d								
PA_0	Exp.	204	2.57	21.1	0.073		***	
PA_3	Exp.	204	2.61	21.1	0.131		***	
PA_5	Exp.	204	2.83	20.8	0.194		***	
Milk solids production, kg/d								
PA_0	Exp.	173	0.165	1.50	0.076		***	
PA_3	Exp.	173	0.167	1.50	0.138		***	
PA_5	Exp.	173	0.185	1.48	0.207		***	
PA_0								
4% FCM production, kg/d	Exp.	190	2.50	20.5	0.082		***	
Milk fat production, kg/d	Exp.	179	0.904	0.82	0.084		***	
Milk protein production, kg/d	Exp.	173	0.074	0.69	0.065		***	
Milk fat concentration, g/kg	Quad.[4]	179	1.08	44.9	−0.19	0.0019	***	**
Milk protein concentration, g/kg	Quad.	173	0.56	29.2	0.12	−0.0010	***	***
Grazing time, min/d	Quad.	66	24.3	415	4.18	−0.033	**	*
Ruminating time, min/d	Lin.[5]	54	17.1	424	0.27		NS	
Pasture intake rate, g of DM/min	Lin.	66	1.31	19.2	0.24		***	
Biting rate, bites/min	Quad.	27	1.2	62	−0.34	0.005	†	*
Bite mass, mg of DM	Quad.	27	25.8	254	11.7	−0.12	**	*

[1]Equation.

[2]a = overall intercept or overall asymptote; b = overall regression linear coefficient or overall exponential coefficient; c = overall regression quadratic coefficient.

[3]Exp. = exponential equation; $R_y = a \times (1 - \exp^{(-b \times PA)}) +$ study, where R_y is the predicted variable y in response to PA change and study is the random effect of the study.

[4]Quad. = quadratic equation; $R_y = a +$ study $+ b \times PA + c \times PA^2$.

[5]Lin. = linear equation; $R_y = a +$ study $+ b \times PA$.

†$P < 0.1$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

or pasture mass (i.e., EH) or to standardized pasture mass at any EH. In fact, the effect of PA on pasture intake may be represented by only one curve when plotting at equivalent PA (i.e., by correcting PA according to EH). Increasing PA from low to medium, or from medium to high, results in the same increase in pasture intake whatever the EH. As EH in the database is, to some degree, linked to country, this suggests that no specific relationship exists for some parts of the world, and infers high portability of the global equations calculated here. This also suggests that the equations used to recalculate pasture mass and PA at any EH are well suited for swards mainly based on perennial ryegrass and perennial ryegrass-white clover, and that the global relationship is not biased.

Milk Production and Composition; Milk Solids

Predictive equations describing the effect of PA on milk production in grazing dairy cows are very scarce in the literature. Single linear (Maher et al., 2003) or quadratic (Delaby et al., 2003) relationships have previously been established from local data sets, but no general equations are available from the literature review. To our knowledge, the exponential increase in milk production with increasing PA is described for the first time, and could be directly related to the exponential relationship found between PA and pasture intake. At PA_5, the average slopes for PA and milk production are very close to those found by Delaby et al. (2003) who observed a 0.32 and 0.08 kg increase in milk production per kilogram of PA between low and medium, and between medium and high PA, respectively. Similarly to pasture intake, the increase in milk production and milk solids production per kilogram of increase in PA is lower for PA_0 than PA_3 or PA_5. The global equations proposed thus enable the effect of PA on milk production to be simulated, irrespective of methodological approach.

Milk production response per kilogram increase in pasture intake is greater from low to medium than from medium to high PA (1.0 vs. 0.7 kg of milk/kg of pas-

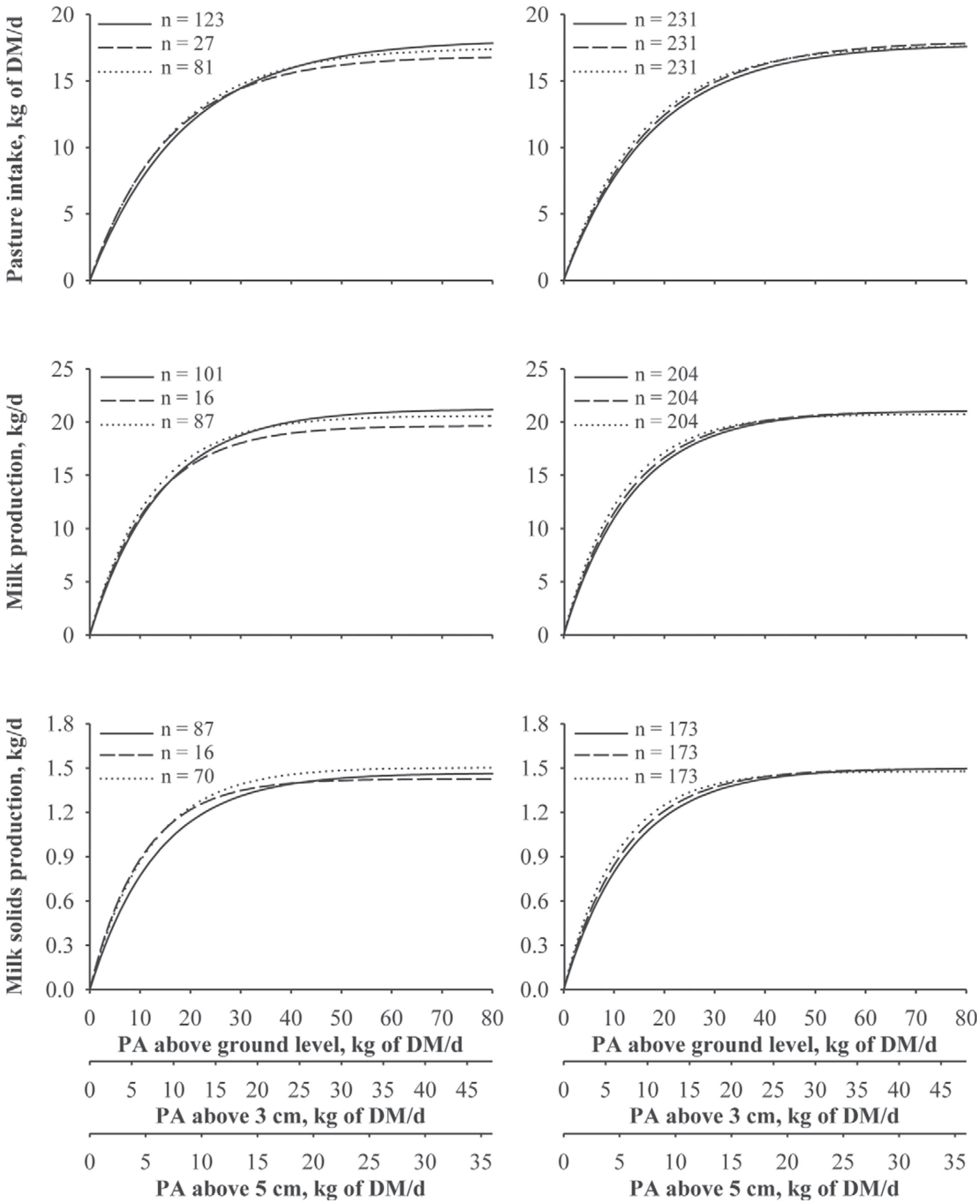

Figure 2. Effect of pasture allowance (PA) on pasture intake, milk production, and milk solids production of grazing dairy cows. Plots on the left report the regression lines calculated within the above-ground-level (PA_0) subset (—), the above-3-cm (PA_3) subset (----), and the above-5-cm (PA_5) subset (····; Table 4). Plots on the right report the regression lines resulting from the global analysis of PA above ground level (—), 3 cm (----), and 5 cm [····; Table 5; $R_y = a \times (1 - \exp^{(-b \times PA)}) +$ study, where R_y is the predicted variable y in response to PA change, a is the overall asymptote, b is the overall exponential coefficient, and study is the random effect of the study]. In the global analysis, PA was recalculated above ground level and above 3 cm when originally reported above 5 cm, and vice versa. Equivalences between PA above ground level, 3 cm, and 5 cm are reported in Table 1.

ture intake DM). This greater efficiency at low than at high PA levels could be mainly explained by the lower energy balance. According to Coulon and Rémond (1991), the marginal response of milk production to intake is lower for well- than under-fed cows (i.e., with high rather than low energy balance). Those authors suggested a metabolic adaptation of cows at low energy balance through a great reduction of energy expenditure and milk production for maintaining homeostasis. This also suggests that the known increase in quality of

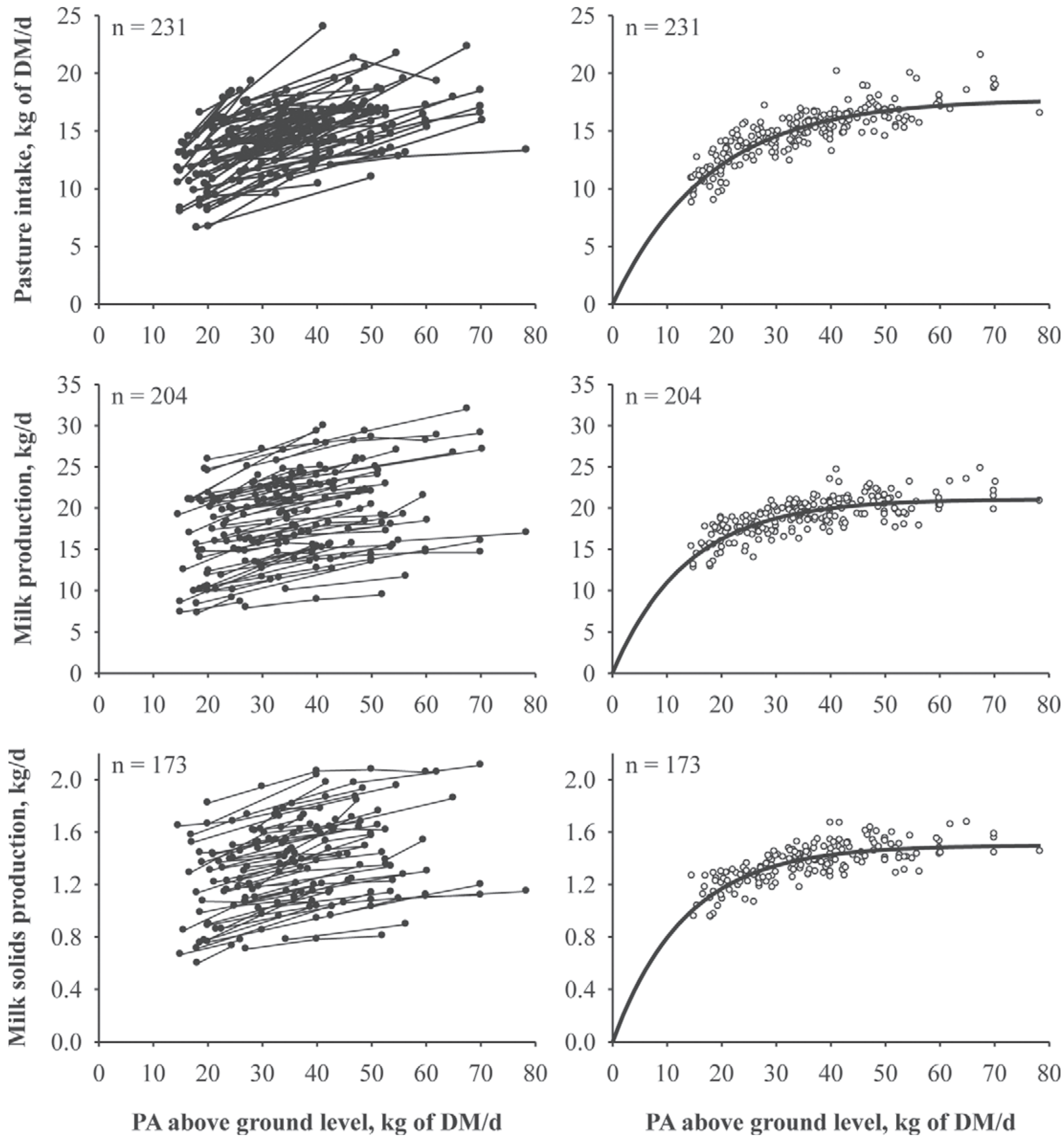

Figure 3. Effect of pasture allowance (PA) on pasture intake, milk production, and milk solids production in grazing dairy cows. Plots on the left report raw data (●) from each study included in the meta-analysis (1 line = 1 PA comparison). Plots on the right report adjusted observations (○) and the mean regression line from the mixed model analysis if $P < 0.10$. The equations are reported in Table 5 [$R_y = \text{a} \times (1 - \exp^{(-\text{b} \times \text{PA})}) + \text{study}$, where R_y is the predicted variable y in response to PA change, a is the overall asymptote, b is the overall exponential coefficient, and study is the random effect of the study]. Low, medium, and high PA correspond to 20, 40, and 60 kg of DM/d, as reported in Table 1.

the selected pasture with increasing PA, due to greater postgrazing sward height (Pérez-Ramírez et al., 2009; Pérez-Prieto et al., 2011b), is of minor importance for explaining milk production variation with PA.

According to the mixed model, milk fat concentration is not affected between high and medium PA, but increases from medium to low PA. The greater milk fat concentration at low PA may be explained by the greater consumption of pseudostem and dead material under severe grazing conditions, increasing the diet fiber concentration (Leaver, 1985). The increase in milk protein concentration is greater from low to medium than from medium to high PA. Indeed, milk protein concentration is positively correlated with energy intake (Coulon and Rémond, 1991), the low variation in milk protein concentration between medium and high PA likely being the consequence of lower variations in energy supply than between low and medium PA. The medium-term PA effects on intake, milk production and milk composition are consistent with the long-term effect of stocking rate reported previously in a meta-analysis by McCarthy et al. (2011).

The exponential effect of PA on milk solids is also described for the first time. It takes into account the

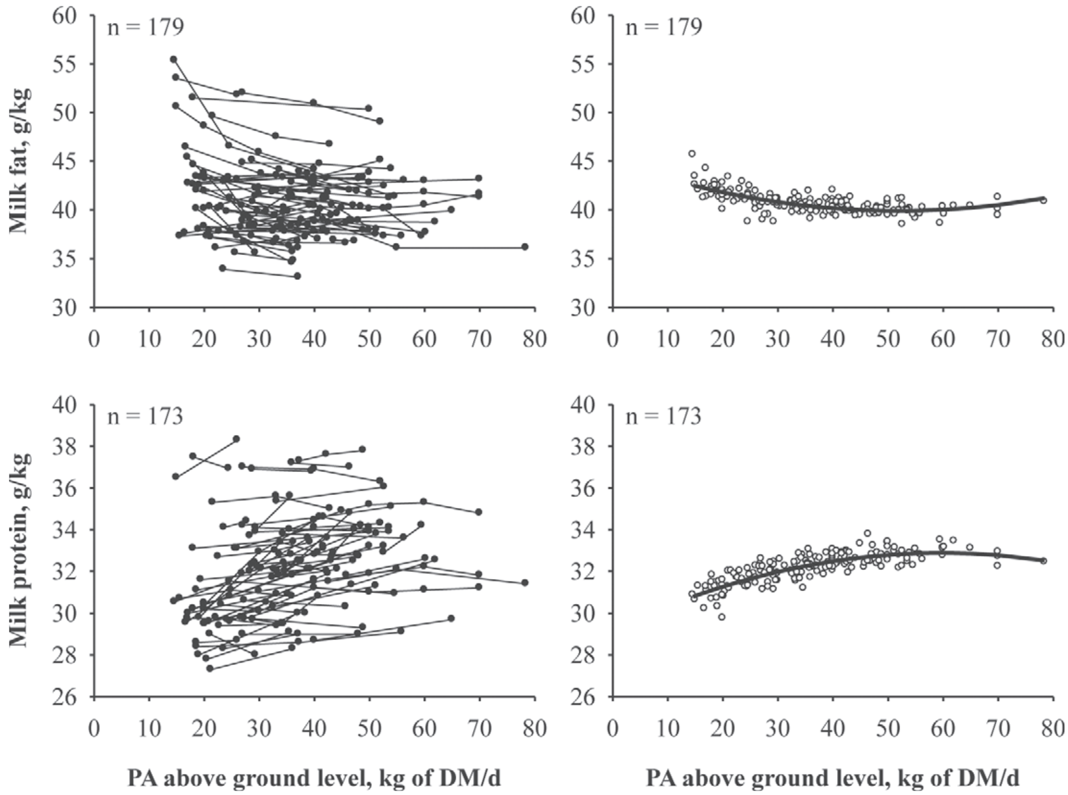

Figure 4. Effect of pasture allowance (PA) on concentrations of milk fat and milk protein in grazing dairy cows. Plots on the left report raw data (●) from each study included in the meta-analysis (1 line = 1 PA comparison). Plots on the right report adjusted observations (○) and the mean regression line from the mixed model analysis if $P < 0.10$. The equations are reported in Table 5 [$R_y = a + \text{study} + b \times \text{PA} + c \times \text{PA}^2$, where R_y is the predicted variable y in response to PA change, a is the overall intercept, study is the random effect of the study, b is the overall regression linear coefficient, and c is the overall regression quadratic coefficient]. Low, medium, and high PA correspond to 20, 40, and 60 kg of DM/d, as reported in Table 1.

various effects of PA on pasture intake, the quality of selected pasture, milk production response, and milk composition. The relative increase in milk solids from low to high PA is of the same extent as that of milk production as a consequence of the opposite variations of milk fat and protein concentrations, which are of the same magnitude.

Behavioral Adaptation to PA Variation

According to the equation calculated in the present meta-analysis, grazing time variations with PA are very small compared with pasture intake variations. Grazing time does not appear as an adjustable variable to maintain pasture intake when reducing pasture availability (i.e., PA). This cow behavior under rotational grazing seems clearly different to that observed under continuously stocked management (Rook et al., 1994; Gibb et al., 1997). In such grazing methods, pasture availability is determined by sward surface height, directly affecting pasture intake rate. The low pasture intake rate at low sward surface height is totally or partially compensated by extending grazing time, sometimes to even more than 650 min/d (Hodgson, 1986). In the present meta-analysis, grazing time decreases and becomes an additional factor reducing pasture intake under severe grazing conditions (i.e., from medium to low PA). In our database, grazing time was rarely longer than 600 min/d under strip- or rotational-grazing management (Bargo et al., 2002; Kennedy et al., 2007a), with most data falling between 450 and 550 min/d. The lack of grazing time extension under severe grazing conditions has to be related to the limited area, which forces cows to graze lower into the sward profile. The cows' motivation is probably reduced due to the grazing of strata richer in pseudostem and dead material and grazing time is limited. The lack of extension of daily grazing time with low leaf availability has already been observed in dairy cows (Delagarde et al., 2010) and sheep (Penning et al., 1994) during the last days of residence time under rotational grazing management, particularly when compared with continuous stocking (Penning et al., 1991). These results confirm that, under strip- or rotational-grazing management, grazing

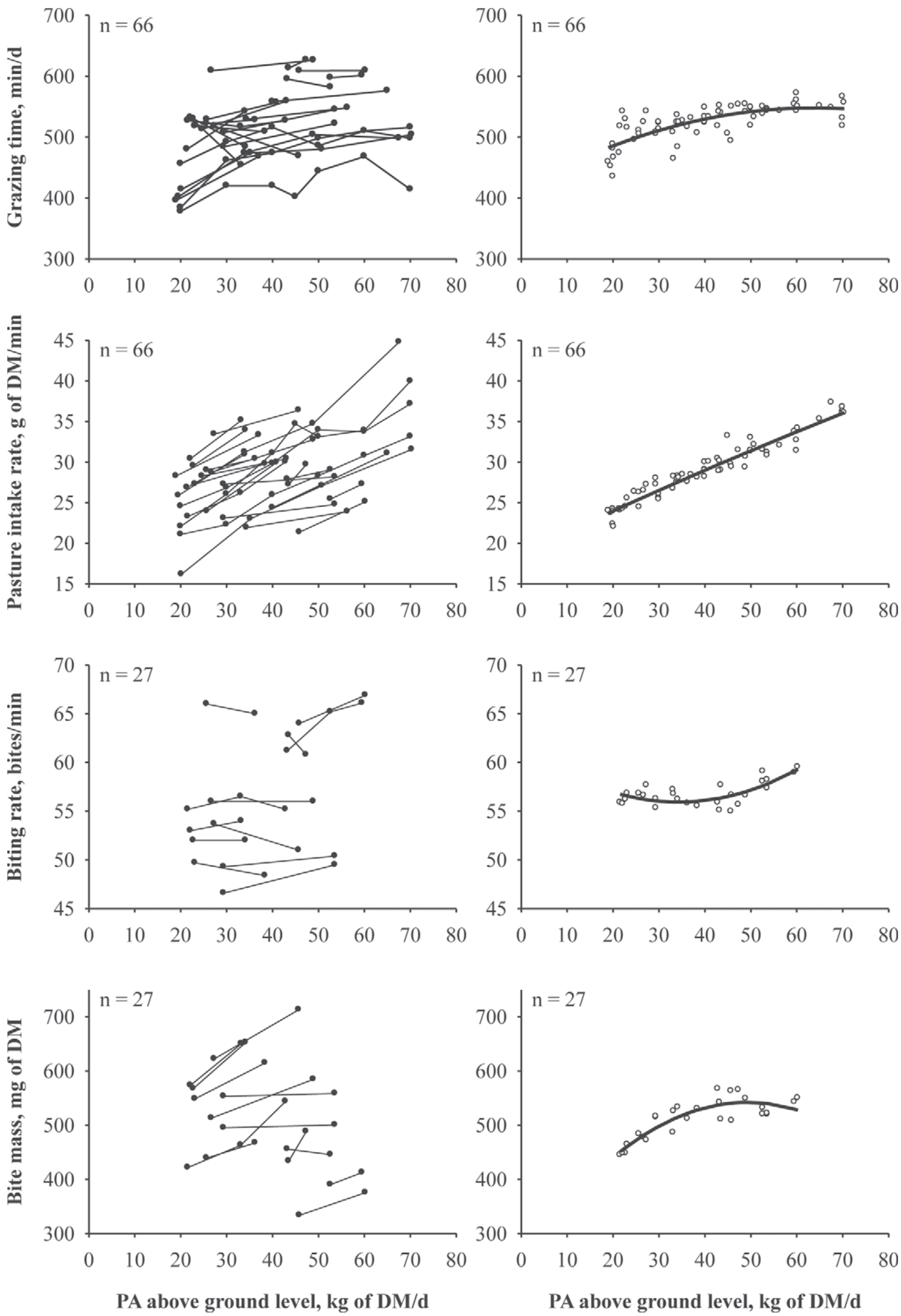

Figure 5. Effect of pasture allowance (PA) on grazing time, pasture intake rate, biting rate, and bite mass in grazing dairy cows. Plots on the left report raw data (●) from each study included in the meta-analysis (1 line = 1 PA comparison). Plots on the right report adjusted observations (○) and the mean regression line from the mixed model analysis if $P < 0.10$. The equations are reported on Table 5 ($R_y = a + \text{study} + b \times \text{PA} + c \times \text{PA}^2$, where R_y is the predicted variable y in response to PA change, a is the overall intercept, study is the random effect of the study, b is the overall regression linear coefficient, and c is the overall regression quadratic coefficient). Low, medium, and high PA correspond to 20, 40, and 60 kg of DM/d, as reported in Table 1.

Table 6. Global analysis of the effect of pasture allowance (PA) and estimation height (EH) on pasture intake, milk production, 4% FCM production, and milk solids production in grazing dairy cows[1]

Item	No. of data	SD	Parameter a	Parameter b	Parameter c	Significance EH	Significance PA
Pasture intake, kg of DM/d	231	1.49	17.8	0.055	0.0146	***	***
Milk production, kg/d	204	2.60	20.9	0.073	0.0192	***	***
4% FCM production, kg/d	190	2.50	20.3	0.080	0.0259	***	***
Milk solids production, kg/d	173	0.166	1.48	0.073	0.0249	***	***
Milk fat production, kg/d	179	0.096	0.81	0.082	0.0257	***	***
Milk protein production, kg/d	173	0.075	0.68	0.061	0.0230	***	***

[1]Equation: $R_y = a \times (1 - \exp^{[-(b + c \times \text{EH}) \times \text{PA}]}) + \text{study}$, where R_y is the predicted variable y in response to PA change, a is the overall asymptote, b is the overall intercept of the linear fixed effect of EH on the exponential coefficient, c is the overall regression linear coefficient of the linear fixed effect of EH on the exponential coefficient, and study is the random effect of the study.

***$P < 0.001$.

time is not used by dairy cows as a determinant adjustment variable to compensate low pasture availability, as previously reported by Pérez-Prieto and Delagarde (2012) in a meta-analysis studying the effect of pregrazing pasture mass on dairy cows.

Data for bite mass and biting rate were scarce and no clear trends were established. According to the results obtained in the global analysis, the reduction in pasture intake rate from medium to low PA should be mainly driven by a reduction in bite mass, with biting rate remaining stable. On the other hand, from medium to high PA, the increase in pasture intake rate seems related to an increase in biting rate because of low variation in bite mass.

Practical Implications

The methodology for determining pasture mass and thus PA varies widely worldwide, due particularly to cutting or EH. This leads to large differences in absolute values for PA recommendations or thresholds limiting pasture intake and performance of grazing dairy cows. The predictive equations of this meta-analysis will allow better determination of adequate PA for grazing management, irrespective of EH, and to understand the differences in PA recommendations according to countries or research teams.

This study also clearly demonstrated that the curves describing the effects of PA on pasture intake, milk production, milk solids or grazing behavior of dairy cows are conceptually the same, whatever the EH, when plotting at equivalent PA (according to EH). From this point of view, the EH at which PA is estimated is not of primary importance, and the global relationship between PA and dependent variables is strong. A global analysis of international data will, however, require the calculation of equivalences between PA estimated at different EH. The equations calculating PA equivalences in Delagarde et al. (2011) were developed from the vertical distribution of pure perennial ryegrass (*Lolium perenne* L.) or ryegrass-white clover (*Trifolium repens* L.) pastures (Delagarde et al., 2000b), which may have biased the estimation of PA effect. However, recalculating PA either at ground level, above 3 cm, or above 5 cm in each subset did not affect the global relationships (Figure 2). This confirms the robustness of this approach for temperate pastures (i.e., those included in our database: mainly grass or grass/clover mixtures). It can be hypothesized that these relationships would be different with others types of pasture, rich in alfalfa or chicory for instance. A standard EH in the grazing research community would, therefore, be interesting to avoid calculations and uncertainty in subsequent global analyses. Previous studies have demonstrated that an EH of 3 cm is a good estimator of the pasture actually available to cows grazing temperate grasslands in a wide range of pregrazing pasture mass (Pérez-Prieto and Delagarde, 2012; Pérez-Prieto et al., 2013). Accordingly, it is recommended to estimate PA above 3 cm, as was already recommended in grazing research for studying the effect of pregrazing pasture mass, or for avoiding misinterpretation of results when comparing pastures differing in pregrazing pasture mass (Pérez-Prieto and Delagarde, 2012; Pérez-Prieto et al., 2013).

The global effects of PA on dependent variables described in this meta-analysis are useful to predict intake, performance, and grazing behavior of strip- or rotational-grazing dairy cows. The asymptotic parameter values reported in the exponential equations, however, correspond to the average grazing conditions and average animal characteristics registered in our database. For example, maximum pasture intake and milk production were approximately 18 kg of DM/d and 21 kg/d, respectively. Greater values have been already recorded with higher-genetic-merit dairy cows during the early stages of lactation or with high pasture quality and ingestibility (Bargo et al., 2002; McCarthy et al., 2007). The equations reported in this meta-analysis become universally applicable when maximum asymptotic values are considered as a potential value, related to animal and pasture quality characteristics. This is the case in previously published models where, for example, intake at grazing is usually reported as a proportion of voluntary intake (i.e., when the same animal is fed ad libitum with the same cut pasture; Sibbald et al., 1979; Freer et al., 1997; Herrero et al., 2000; Delagarde et al., 2011). In this case, only the part of the equation describing the effect of PA has to be used, describing the relative variation of the dependent variable. Dependent variables in this meta-analysis were not reported as a proportion of potential intake or performance because large amounts of data would be lost as a consequence of the lack of information to calculate maximum potential values.

CONCLUSIONS

The present meta-analysis demonstrated that the general relationship between PA and pasture intake, milk production and composition, and grazing behavior of dairy cows is strong and EH independent. The equations reporting the response of dependent variables per kilogram increase in PA are specific for each EH, but describe a common curve, irrespective of EH. Pasture intake, milk production, and milk solids production increase at a declining rate with increasing PA, and are well correlated with grazing behavior variables. Variations in pasture intake according to PA are strongly related to pasture intake rate from low to medium PA, and to grazing time from medium to high PA. It can be concluded that the large range in dairy cow responses to PA variations observed in the literature is largely explained by research methodology (EH), and that this global meta-analysis allows reconciling these conceptual approaches for better predicting intake, milk production, and behavior of grazing dairy cows.

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