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Meta-analysis of the impact of stocking rate on the productivity of pasture-based milk production systems

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The objective of this study is to quantify the milk production response per cow and per hectare (ha) for an incremental stocking rate (SR) change, based on a meta-analysis of published research papers. Suitable experiments for inclusion in the database required a comparison of at least two SRs under the same experimental conditions in addition to details on experimental length and milk production results per cow and per ha. Each additional increased SR treatment was also described in terms of the relative milk production change per cow and per ha compared to the lower base SR (b_SR). A database containing 109 experiments of various lengths with 131 comparisons of SR was sub-divided into Type I experiments (common experimental lengths) and Type II experiments (variable experimental lengths). Actual and proportional changes in milk production according to SR change were analysed using linear mixed model procedures with study included as a random effect in the model. Low residual standard errors indicated a good precision of the predictive equations with the exception of proportional change in milk production per cow. For all milk yield variables analysed, the results illustrate that while production per cow is reduced, a strong positive relationship exists between SR and milk production per ha. An SR increase of one cow/ha resulted in a decrease in daily milk yield per cow of 7.4% and 8.7% for Type I and Type II data, respectively, whereas milk yield per ha increased by 20.1% and 19.6%, respectively. Within the Type II data set, a one cow/ha increase in SR also resulted in a 15.1% reduction in lactation length (equivalent to 42 days). The low predictability of proportional change in milk production per cow according to the classical SR definition of cows per ha over a defined period suggests that SR may be more appropriately defined in terms of the change in available feed offered per animal within each treatment.

Keywords: dairy cow, stocking rate, pasture-based systems, meta-analysis

Implications

This study found that a one cow/ha increase in stocking rate (SR) reduced milk production per cow by 8.7%, whereas production per hectare (ha) was increased by 19.6%. The results indicate that the classical definition of SR as animals per unit area of land (cows per ha) is inadequate to describe the effect of an SR change on milk production per cow. The results suggest that SR treatments may be defined as feed or energy available per cow, whereas the effects of an SR change may be characterised as the change in feed or energy supply to animals within each treatment.

Introduction

One of the primary objectives of pasture-based dairy producers is to maximise profitability per hectare (ha) of grazing land through increased pasture production and utilisation (Dillon *et al.*, 2008). Improvements in management within such systems have resulted in large increases in milk production per ha in experimental herds. For example, Horan *et al.* (2005) reported annual production of 15 000 kg milk/ha from <500 kg of concentrates per cow. The main interrelating factors responsible for this increase in productivity appear to be the stocking rate (SR) and calving date (Dillon *et al.*, 1995; Macdonald *et al.*, 2008), nitrogen (N) fertilisation (Delaby *et al.*, 1998; McGrath *et al.*, 1998) and concentrate supplementation (Bargo *et al.*, 2002). SR, traditionally defined as the number of animals fed per unit area of land during a defined period (cows per ha), is widely accepted as the most important factor governing milk output per cow and per unit area from pasture (Mott, 1960; McMeekan, 1964; Penno, 1999). The balance between feed supply and demand as influenced by SR, and to a lesser extent by calving date, is critical because an imbalance will result in either underfeeding

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of the herd or waste of excess feed. In grazing systems, this interaction is further complicated as over/undergrazing of the pasture will result in reduced growth, senescence or reduced nutritional value of the main feed supply (Holmes *et al.*, 2002).

Previous research has indicated that an SR increase results in an increase in milk production per ha, but a decrease in milk production per cow (McMeekan and Walshe, 1963; Hoden *et al.*, 1991). The most recent SR experiment undertaken by Macdonald *et al.* (2008) reported that all per cow milk production variables, with the exception of fat and lactose content, declined linearly with increasing SR. The authors summarised that the reduction in per cow yield variables was due to the shortening lactation length and the lower peak and poorer persistency associated with increased SR and was a consequence of a lower total amount of feed available per cow, as more cows were carried on the same area.

SR determines how much of the available herbage is eaten by the herd, with a greater percentage of the available herbage harvested by the herd at increased SRs (McMeekan, 1964). Macdonald *et al.* (2008) indicated a positive effect of increasing SR on milk yield per ha, irrespective of the effect on milk yield per cow. However, results from a single experiment will not provide a definitive understanding of the effect of SR treatment because the conditions under which observations are made in a single experiment are inevitably narrow (Sauvant *et al.*, 2008). A meta-analysis approach (Glass, 1976), summarising the results across published studies in a particular area and in combination with new statistical techniques, allows increased precision of analysis of effects across multiple experiments (St-Pierre, 2001; Sauvant *et al.*, 2008; Lean *et al.*, 2009). In a historical review of SR experiments, Journet and Demarquilly (1979) reported that an SR increase of one cow/ha resulted in a mean reduction in milk production per cow of 10%, but an increase in production per ha of over 20%. Increased interest in pasture-based production systems internationally, coupled with the increased volume of research data from modern SR experiments now available, requires that the likely effect of an SR change on milk production be revisited. The objective of this study, therefore, is to quantify the milk production response per cow and per ha associated with an SR change, from a low SR, based on a meta-analysis of experiments from 1960 to 2008, taking cognisance of changes in management systems such as grazing management practice, supplementation strategy, lactation length and dairy cow characteristics.

Material and methods

Database design, construction and calculations

The database is best conceptualised with rows representing treatments or groups, whereas the columns initially consist of measured variables (those for which least square means are reported) in addition to treatment characteristics (class levels). Each experiment was allocated an individual experimental code (IdExp). For consideration within the database, an experiment had to contain a comparison of at least two SRs under the same experimental conditions. Where a sub-factor was applied to each SR (e.g. different supplementation or N fertilisation levels) or multiple years of data were reported, each individual SR response result was entered individually. Required experimental data included experimental length, grazing cow-days/ha, the various SR, milk production and bodyweight (BW) results per cow and per ha. Occasionally, measured variables such as grazing cow-days/ha or SR were not reported and were subsequently calculated according to formulas:

$$\text{Grazing cow-days/ha} = [\text{number of cows} \times \text{grazing experiment length}] / \text{maximum area used during grazing experiment (ha)}. \quad (1)$$

$$\text{Stocking rate} = [(\text{grazing cow-days/ha})/\text{grazing experiment length}]. \quad (2)$$

The database contained a number of variables that were not consistently reported in each experiment. Frequently, only milk yield per cow per day was reported, and milk yield per ha was then derived according to the formula:

$$[\text{Grazing cow-days/ha} \times \text{milk yield/cow per day} = \text{milk yield/ha}] \quad (3)$$

As the objective of the study was to analyse the effect of an SR increase from a low SR, within the database, the lowest SR treatment within each experiment was considered the base SR (b_SR), with the milk production at this SR considered as base milk production. The choice of variable to standardise measurement methods across experiments is very important within this analysis to identify the true effect of an SR change, across a diverse group of experiments exhibiting large variation in both systems and animals. For this reason, in addition to the actual reported production, each additional increased SR treatment was described in terms of the relative milk production change per cow per ha compared to the base group. This new variable removed the effect of variation in base performance, experimental length and amount of supplementary feed usage between studies. On review of the experimental evidence, large variability in animal BW was observed both over time and also between experiments. Consequently, to account for this variability and the likely impact on maintenance requirements, in studies where BW information was reported, each SR was also described in terms of BW/ha within the analysis according to the equation:

$$\text{BW/ha} = [\text{BW/cow} \times \text{SR}]. \quad (4)$$

The effect of an SR change was therefore also described in terms of an additional 100 kg BW/ha. As consistent feed supply data (herbage and total dry matter allowances) were unavailable from the reviewed papers, the change in the energy status per cow across treatments was described according to the energy supply within the b_SR treatment of each experiment (estimated according to the energy requirements for maintenance and production using the net energy system (Faverdin *et al.*, 2007)), divided by the increased SR to reflect the reduction in energy status of each cow within an increased SR treatment. This new variable represented the change in energy status of the individual animal according to SR change.

The final database contained 44 papers and 109 experiments published between 1960 and 2008, with 131 comparisons of base *v.* experimental SR used in the final analysis. The mean experiment was 228 days in duration, with 55 cows and a mean SR of 3.7 cows/ha (1879 kg BW/ha). A range of experimental designs was represented in the database including 94 continuous and 10 Latin square designs. The majority of studies used in the database were from Ireland, New Zealand, Australia, France or the United Kingdom.

For analytical purposes, two main subsets of data were created. In common experimental length (Type I) experiments, the experimental period was common to all SRs within the respective experiment (36 papers and 91 experiments), that is, the length of time that each SR within an experiment was applied was the same, with the SR effects observed due to variations in consistently applied feed allowances. Type I experiments reflect the stocking intensity during the grazing season and contain both short- and long-term experiments. These long-term stocking intensity experiments, however, did not cause differences in experimental lengths for the different stocking intensities within that experiment. In variable length (Type II) experiments (eight papers and 18 experiments), the length of the experimental period varied between SR treatments within the respective experiment. These Type II experiments reflect the overall SR at farm level and are therefore a truer reflection of the effect of SR, incorporating both the effects of a reduced herbage allowance and an associated reduction in lactation length.

Statistical analysis

A study effect (IdExp) representing the variance between studies not accounted for by the variables in the model was included in each model, as described by St-Pierre (2001) and more recently by Sauvant *et al*. (2008). The actual change of independent variable in milk production according to SR change was continuous in nature and analysed using linear mixed models by the statistical procedures software of SAS (Proc MIXED, Statistical Institute, 2006), with IdExp included as a random effect and an unstructured variance–covariance structure among records according to the equation:

$$R_y = a + \mathrm{IdExp}_i + b \times \mathrm{SR} + c \times \mathrm{SR}^2 \qquad (5)$$

where, R_y is the predicted production of variable y in response to SR change, a is the intercept, IdExp is the study effect ($i = 1$ to 91 for Type I and 1 to 18 for Type II experiments), b represents the linear coefficient and c represents the quadratic coefficient. Where c was observed to be greater than $P = 0.10$, it was removed from the analysis.

The predicted proportional change in milk production (P_y) was created using the statistical procedures software of SAS (Proc MIXED, Statistical Institute, 2006) according to the equation:

$$Py = a + b \times b\_X + c \times \mathrm{b\_SR} + d \times \mathrm{d\_SR} \qquad (6)$$

where, P_y is the proportional change in variable y according to SR change (d_SR), base milk production per cow (b_X) and b_SR, a is the intercept, b represents the coefficient for the base milk production per cow, c represents the coefficient for the b_SR and d represents the coefficient for SR change. Where b, c and d were observed to be greater than $P = 0.10$, they were removed from the analysis, with the exception of b_SR ($P = 0.115$) for proportional change in milk yield per cow and b_SR ($P = 0.118$) for proportional change in lactose yield per cow, which were kept in the model.

Results

The mean experimental characteristics, production per cow per ha for each data set (Type I and Type II) are outlined in Table 1. Experimental characteristics for both the Type I and Type II data sets are calculated based on milk yield, as this variable contains the greatest number of data points in the Type I data set. The mean SR of the Type I data was 3.8 cows/ha, with a mean daily milk yield per cow and per ha of 17.5 and 9751 kg, respectively. The mean experimental length, grazing cow-days/ha and number of cows used in experiments was 168, 582 days and 52 cows, respectively. Within the Type II data set, the mean SR was 2.8 cows/ha, which resulted in a mean daily milk yield per cow and per ha of 15.0 and 11 115 kg, respectively. The mean grazing cow-days/ha and number of cows used in the experiments was 739 days and 83 cows, respectively. The mean lactation length of experiments within the Type II data set was 272 days.

Effect of increasing SR and BW/ha on milk production for Type I data

The total number of data comparisons for milk production was 121 for SR expressed as cows per ha and 90 for SR expressed as 100 kg BW/ha. The effect of a one cow/ha increase in SR and a 100 kg increase in BW/ha on milk production per cow and per ha for Type I data is outlined in Table 2. Mean daily milk and milk solids (fat + protein; MS) yield per cow for the b_SR were 18.1 and 1.33 kg, respectively. For all milk yield variables analysed, production per cow reduced ($P < 0.05$) and milk production per ha increased ($P < 0.05$), when SR increased by one cow/ha and BW/ha by 100 kg. Within the Type I data in which experimental length was common to all SRs, mean daily milk and MS yield per cow were reduced by 1.23 and 0.08 kg, respectively, whereas milk and MS yield per ha were

Table 1 *Mean production data for the database for Type I[a] and Type II[b] experimental data*

	Type I					Type II				
	Number of data	Mean	s.d.	Minimum	Maximum	Number of data	Mean	s.d.	Minimum	Maximum
Experimental characteristics (milk yield database)										
Number of cows	190	52	26	12	117	33	83	30	40	116
Stocking rate (cows/ha)	190	3.83	1.7	0.9	10.0	33	2.8	0.8	1.3	4.5
Experimental length (days)	190	168	6.7	46	305					
Lactation length (days)						33	272	27	221	316
Grazing days per ha (days)	190	582	254	87	1273	33	739	177	361	1013
BW (kg/cow)	146	497	89.8	278	686	28	500	77.6	322	638
BW (kg/ha)	146	1946	883	306	5160	28	1532	283	1071	2150
Production per cow (kg)										
Milk yield	190	17.5	5.1	4.8	31.6	33	15.0	2.1	11.1	18.6
Fat yield	159	0.690	0.194	0.17	1.16	45	0.65	0.09	0.45	0.800
Protein yield	134	0.596	0.179	0.13	1.07	25	0.55	0.05	0.47	0.631
Lactose yield	85	0.901	0.190	0.58	1.48	15	0.76	0.09	0.55	0.838
MS[c] yield	132	1.294	0.386	0.31	2.22	30	1.28	0.08	1.14	1.470
Fat content[d]	159	40.6	6.45	32.0	59.5	33	44.4	7.7	35.6	63.3
Protein content[d]	134	32.7	2.15	27.9	40.4	25	35.8	3.0	33.4	43.9
Lactose content[d]	85	46.5	2.01	43.5	54.1	15	46.6	1.8	44.2	49.0
Production per hectare (kg)										
Milk yield	190	9751	4216	1580	18 802	33	11 115	2888	4954	14 828
Fat yield	159	385	172	71	765	45	514	146	187	747
Protein yield	134	348	145	51	648	25	448	40	370	518
Lactose yield	85	567	173	168	876	15	608	50	537	722
MS yield	132	760	313	122	1413	30	1039	109	843	1265

MS = milk solids.
[a]Type I = common length experiments.
[b]Type II = variable length experiments.
[c]MS = fat + protein.
[d]Values are expressed in g/kg.

increased by 1657 and 113 kg, respectively. A one cow/ha SR increase resulted in a decrease in daily milk, fat, protein, lactose and MS yield per cow of 7.4%, 6.3%, 8.2%, 6.8% and 7.0%, respectively, and an increase in milk, fat, protein, lactose and MS yield per ha of 20.1%, 21.0%, 16.9%, 16.2% and 18.5%, respectively. The impact of a one cow/ha SR increase was not consistent for fat, protein and lactose content, as milk fat content was increased by 1.2%, whereas milk protein and lactose content were reduced by 1.5% and 0.5%, respectively. An increase in BW/ha of 100 kg reduced per cow yields for milk production variables by a mean value of 1.52%, whereas per ha yields increased by 3.72%. As with a one cow/ha SR increase, a 100 kg increase in BW/ha increased milk fat content and reduced milk protein and lactose content.

Effect of increasing SR and BW/ha on milk production for Type II data

Table 3 describes the effect of a one cow/ha increase in SR and a 100-kg increase in BW/ha on milk production per cow and per ha for Type II data. Mean daily milk and MS were 15.8 and 1.37 kg, respectively. Similar to the results for Type I data, a one cow/ha increase in SR and a 100 kg increase in BW/ha reduced milk production per cow ($P < 0.05$) and increased milk production per ha ($P < 0.05$) for Type II data. Within the Type II data set, a one cow/ha SR increase reduced lactation length by 15.1% (equivalent to 42 days). A one cow/ha SR increase resulted in a reduction in daily milk and MS yield of 1.38 and 0.13 kg/cow, whereas increasing milk and MS yield per ha by 1568 and 101 kg, respectively. The reduction in daily milk yield variables per cow was greater, when compared to Type I data, as daily milk, fat, protein, lactose and MS were reduced by 8.7%, 6.9%, 9.8%, 6.9% and 9.2%, respectively. In comparison with the Type I data set, the increase in milk production per ha due to a one cow/ha SR increase in the Type II data set were less, with daily milk, fat, protein, lactose and MS yield per ha increases of 19.6%, 14.0%, 10.1%, 11.4% and 11.4%, respectively. Milk fat and lactose content were unaffected by a one cow/ha SR increase, whereas protein content was reduced by 1.9%. A 100-kg increase in BW/ha decreased lactation length by 2.69% (equivalent to 7.8 days). Similar to a one cow/ha increase in SR, daily milk yield per cow variables were reduced to a greater extent for Type II data compared to Type I data, whereas the increase in milk yield per ha variables was less. Mean daily milk yield variables per cow declined by 2.02% and milk yield per ha variables increased by 2.84%. Increasing BW/ha by 100 kg had no effect on milk fat and lactose content, whereas milk protein content was reduced by 0.43%.

Table 2 *Change in experimental length, milk production per cow and per ha for an increase in stocking rate of one cow/ha for and 100 kg BW/ha for Type I[a] experimental data*

	One cow/ha				100 kg BW/ha			
	Number of data	Base	Actual change (kg)	Proportional change (%)	Number of data	Base	Actual change (kg)	Proportional change (%)
Experimental characteristics								
Experimental length (days)	99	170			75	168		
Lactation length (days)								
BW (kg/cow)					75	504		
BW (kg/ha)					75	1719	447	25.3
Production per cow (kg)								
Milk yield	99	18.1	−1.228***	−7.42***	75	18.7	−0.264***	−1.55***
Fat yield	83	0.71	−0.040***	−6.32***	71	0.74	−0.009***	−1.37***
Protein yield	70	0.62	−0.046***	−8.21***	60	0.65	−0.011***	−1.78***
Lactose yield	43	0.93	−0.063***	−6.81***	40	0.94	−0.013***	−1.40***
MS[b] yield	69	1.33	−0.082***	−6.97***	59	1.40	−0.019***	−1.47***
Fat content[c]	83	40.2	0.434**	1.23**	71	40.4	0.113**	0.31***
Protein content[c]	70	32.9	−0.507***	−1.53***	60	33.2	−0.124***	−0.38***
Lactose content[c]	43	46.6	−0.234**	−0.50**	40	46.7	−0.055**	−0.12**
Production per hectare (kg)								
Milk yield	99	8868	1657***	20.1***	71	9303	358***	3.97***
Fat yield	83	348	69***	21.0***	60	364	15***	4.35***
Protein yield	70	317	47***	16.9***	40	343	10***	3.21***
Lactose yield	43	527	77***	16.2***	71	542	17***	3.40***
MS yield	69	689	113***	18.5***	60	742	26***	3.65***

MS = milk solids.
[a]Type I = common length experiments.
[b]MS = fat + protein.
[c]Values are expressed in g/kg.
** = $P < 0.01$.
*** = $P < 0.001$.

Table 3 *Change in experimental length, milk production per cow and per ha for an increase in stocking rate of one cow/ha and 100 kg of BW/ha for Type II[a] experimental data*

	One cow/ha				100 kg BW/ha			
	Number of data	Base	Actual change (kg)	Proportional change (%)	Number of data	Base	Actual change (kg)	Proportional change (%)
Experimental characteristics								
Experimental length (days)								
Lactation length (days)	32	284	−42.0***	−15.1***	19	293	−7.80***	−2.69***
BW (kg/cow)					19	505		
BW (kg/ha)					19	1193	445***	39.7***
Production per cow (kg)								
Milk yield	22	15.8	−1.38***	−8.66***	15	16.8	−0.32***	−1.87***
Fat yield	28	0.68	−0.05***	−6.93***	15	0.76	−0.02***	−2.11***
Protein yield	16	0.59	−0.06***	−9.84***	15	0.59	−0.01***	−2.26***
Lactose yield	9	0.79	−0.06*	−6.91*	9	0.79	−0.02*	−1.85*
MS[b] yield	20	1.37	−0.13***	−9.15***	19	1.38	−0.03***	−2.02***
Fat content[c]	22	44.1	−0.23[ns]	−0.41[ns]	15	45.7	−0.11[ns]	−0.25[ns]
Protein content[c]	16	36.0	−0.71**	−1.90**	15	35.5	−0.16**	−0.43**
Lactose content[c]	9	46.8	0.18[ns]	0.37[ns]	9	46.8	0.05[ns]	0.10[ns]
Production per hectare (kg)								
Milk yield	22	9878	1568***	19.63***	15	11 573	335***	3.07***
Fat yield	28	474	42**	13.98**	15	526	14**	2.80**
Protein yield	16	417	38**	10.14**	15	410	10**	2.58**
Lactose yield	9	570	61*	11.37*	9	570	16*	3.04*
MS yield	20	957	101***	11.36***	19	941	24***	2.69***

MS = milk solids.
[a]Type II = variable length experiments.
[b]MS = fat + protein.
[c]Values are expressed in g/kg.
* = $P < 0.05$.
** = $P < 0.01$.
*** = $P < 0.001$.
[ns] = $P > 0.05$.

The prediction of milk production according to SR change (Type I experimental data) and lactation length (Type II experimental data)

The equations that accounted for the greatest proportion of variation in predicted milk production per cow and per ha are described in Table 4 (and Figure 1). The residual standard error (r.s.e.) is low at 0.73 for milk yield, indicating a good precision of the predictive equations. With the exception of milk, protein and MS yield per cow and lactose content, quadratic equations accounted for the greatest proportion of the variance. On the basis of the predictive equations in Table 4, a one cow/ha SR increase resulted in a mean proportional reduction of 4.9%, 5.6%, 5.9%, 8.6% and 5.0% for daily milk, fat protein, lactose and MS yield per cow, respectively, whereas increasing yield per ha by 26.3%, 24.7%, 22.3%, 22.1% and 23.7%, respectively.

Predictive equations for daily milk yield per cow variables and milk yield per ha variables as a function of BW/ha are shown in Table 5. All equations were quadratic. On the basis of the predictive equations in Table 5, a 100-kg increase in BW/ha resulted in a mean proportional reduction of 1.5%, 1.3%, 1.9%, 1.6% and 1.7% for daily milk, fat, protein, lactose and MS yield per cow, respectively, whereas increasing production per ha by 5.8%, 5.7%, 4.9%, 4.8% and 5.2%, respectively. Similar to the effect of an SR change, all daily milk production variables, with the exception of fat content, declined while milk production per ha increased when BW/ha increased by 100 kg. The slope of the equations generated differs from those calculated according to a one cow/ha SR increase (Table 4), indicating a possible interaction between animal size and milk production response to an SR change. This effect has previously been observed (Ahlborn and Bryant, 1992; Holmes *et al.*, 1993) and is further substantiated by Lopez-Villalobos *et al.* (2008) using data from Irish pasture-based systems. These authors suggested that increased feed conversion efficiency among phenotypically lighter cows was responsible for increased MS production at greater SRs in comparison with heavier cows.

The predicted effect of SR on lactation length was derived from Type II data using the following equation:

$$\text{Lactation length (days)} = 389 + (-40.2 \times \text{SR}) \quad (7)$$

The prediction equation (r.s.e. = 12.5) indicates that a one cow/ha increase in SR will result in a 40-day decline in lactation length. Predictive equations for daily milk production per cow and per ha were derived separately for experiments differing in lactation length (Type II experimental

Table 4 *Effect of SR on milk production variables for Type I[a] experimental data*

Type I	Equation: $R_y = a + \text{IdExp}_i + b \times \text{SR} + c \times \text{SR}^2$ Number of data	r.s.e.	*a*	*b*	*c*
Production per cow (kg)					
Milk yield	190	0.73	20.94	−0.911	
Fat yield	159	0.03	0.872	−0.061	0.003
Protein yield	134	0.02	0.762	−0.039	
Lactose yield	85	0.03	1.342	−0.139	0.008
MS[b] yield	132	0.05	1.599	−0.071	
Fat content[c]	159	0.97	46.12	−2.762	0.298
Protein content[c]	134	0.45	35.62	−0.895	0.049
Lactose content[c]	85	0.36	47.42	−0.212	
Production per hectare (kg)					
Milk yield	190	420	1763	2587	−104.91
Fat yield	159	25	92.10	89.31	−2.77
Protein yield	134	20	86.82	81.74	−3.89
Lactose yield	85	22	152.79	116.1	−4.22
MS yield	132	45	173.01	178.8	−7.57

SR = stocking rate; MS = milk solids.
$R_y = a + \text{IdExp}_i + b \times \text{SR} + c \times \text{SR}^2$, where: a = origin, IdExp = experimental effect, b = linear coefficient and c = slope.
[a]Type I = common length experiments.
[b]MS = fat + protein.
[c]Values are expressed in g/kg.

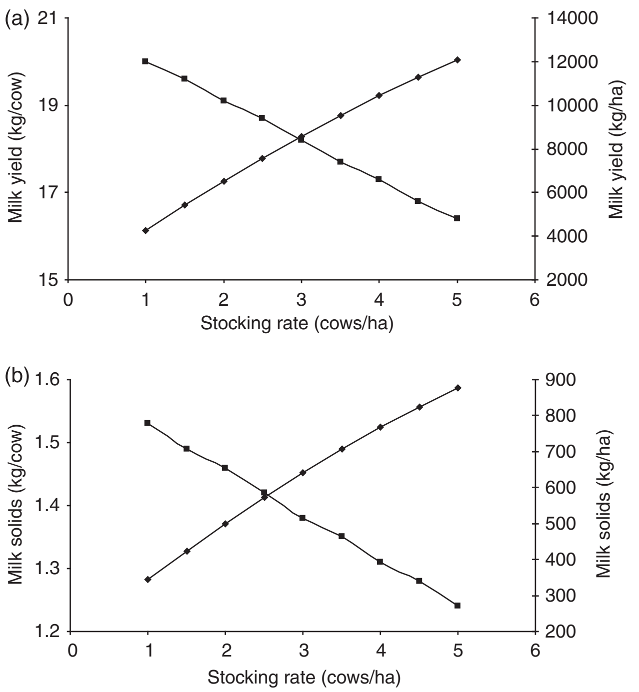

Figure 1 Effect of a change in stocking rate on (a) milk production per cow (■) and per hectare (ha) (◆) and (b) milk solids per cow (■) and milk solids per ha (◆) according to stocking rate (Type I experimental data).

data; Table 6). On the basis of these equations, a one cow/ha SR increase will result in a mean reduction of 5.3% and 7.4% in milk and MS production per cow, respectively, while increasing milk and MS yield per ha by 17.3% and 13.1%, respectively. The reduction in lactation length observed within Type II data has been observed previously. MacDonald *et al.* (2008) attributed a large portion of the reduction in milk production per cow to a reduction in lactation length, while Holmes *et al.* (1993) similarly reported a shortening of lactation length at increased SRs due to reduced feed supply and a requirement for an extended dry interval among animals of reduced body condition score.

The prediction of milk production according to base production per cow, b_SR and SR change (Type I experimental data)

Predicted proportional change in milk production per cow and per ha is described in Table 7 according to base group productivity per cow, b_SR and SR change. In this analysis, the base production variable was not significant ($P > 0.10$) when describing the proportional change in production (P_y) for fat, protein and lactose content per cow; protein and lactose yield per ha and was therefore excluded for these variables. The b_SR was not significant ($P > 0.15$) when describing the proportional change in production (P_y) for protein and MS yield per cow and was also removed from these equations. For a one cow/ha SR increase from a b_SR of 3.5 cows/ha, the proportional reduction in milk, fat, protein, lactose and MS yield per cow was 7.1%, 6.0%, 8.4%, 6.3% and 7.1%, respectively, whereas the proportional increase per ha was 19.3%, 20.5%, 17.6%, 18.4% and 19.0%, respectively. These effects correspond to a 1.3% increase in fat content and a reduction of protein content of 1.6%, while lactose content was unaffected.

Discussion

The results of this analysis further illustrate the strong positive relationship between SR and milk production per ha (Hoden *et al.*, 1991; Macdonald *et al.*, 2008) while the

Table 5 *Effect of BW/ha on milk production variables for Type I[a] experimental data*

Type I	Equation: $R_y = a + \text{IdExp}_i + b \times \text{BW/ha} + c \times \text{BW/ha}^2$				
	Number of data	r.s.e.	*a*	*b*	*c*
Production per cow (kg)					
Milk yield	146	0.60	23.87	−0.0041	4.42×10^{-7}
Fat yield	139	0.03	0.897	−0.0001	1.61×10^{-8}
Protein yield	117	0.02	0.926	−0.0002	2.18×10^{-8}
Lactose yield	80	0.03	1.304	−0.0002	2.44×10^{-8}
MS[b] yield	115	0.04	1.941	−0.0004	4.91×10^{-8}
Fat content[c]	139	0.90	44.41	−0.0040	9.27×10^{-7}
Protein content[c]	117	0.44	36.53	−0.0023	2.79×10^{-7}
Lactose content[c]	80	0.37	47.27	−0.0007	6.07×10^{-8}
Production per ha (kg)					
Milk yield	146	467	1700	5.23	-3.6×10^{-4}
Fat yield	139	19	80	0.19	-1×10^{-5}
Protein yield	117	17	96	0.16	-1×10^{-5}
Lactose yield	80	19	137	0.24	-2×10^{-5}
MS yield	115	35	185	0.35	-2×10^{-5}

MS = milk solids.
$R_y = a + \text{IdExp}_i + b \times \text{BW/ha} + c \times \text{BW/ha}^2$, where: a = origin, IdExp = experimental effect, b = linear coefficient and c = slope.
[a]Type I = common length experiments.
[b]MS = fat + protein.
[c]Values are expressed in g/kg.

Table 6 *Effect of SR and Laclgt on milk yield per cow and per ha (Type II[a] experimental data)*

Type II	Equation: $R_y = a + \text{IdExp}_i + b \times \text{SR} \times \text{Laclgt}$			
	Number of data	r.s.e.	*a*	*b*
Production per cow (kg)				
Milk yield	33	0.55	19.34	−0.0053
Fat yield	45	0.03	0.886	−0.0003
Protein yield	25	0.02	0.828	−0.0003
Lactose yield	15	0.03	1.051	−0.0004
MS[b] yield	30	0.04	1.836	−0.0007
Fat content[c]	33	1.17	48.79	−0.0047
Protein content[c]	25	0.58	40.04	−0.0046
Lactose content[c]	15	0.21	45.17	0.0010
Production per hectare (kg)				
Milk yield	33	407	3185	10.58
Fat yield	45	22	184	0.428
Protein yield	25	18	210	0.286
Lactose yield	15	28	246	0.417
MS yield	30	38	432	0.722

SR = stocking rate; Laclgt = lactation length; MS = milk solids.
$R_y = a + \text{IdExp}_i + b \times \text{SR} \times \text{Laclgt}$, where: IdExp = experimental effect, a = origin, b = slope.
[a]Type II = variable length experiments.
[b]MS = fat + protein.
[c]Values are expressed in g/kg.

consistently low r.s.e. observed within these results emphasise the appropriateness of the techniques applied in this study. Castle *et al.* (1972) reported that over 19 years, SR and milk yield per cow explained 85% of the variation in total milk production. The impact of a one cow/ha SR increase on milk production per ha within the current data set (20.1% and 19.6% for Type I and Type II experiments, respectively) is similar to the findings of Journet and Demarquilly (1979) when comparing raw mean effects on similar data. McMeekan and Walshe (1963) considered that the optimum SR is such that the reduction in production per cow is 10% to 12% of the potential production obtained at a low SR. Within the context of the current data set, the observed reduction in milk production per cow of 7.4% and 8.7% for

Table 7 *Effect of b_X/cow, b_SR and d_SR on the* P_y *in milk production (Type I*[a] *experimental data)*

Type I	Number of data	r.s.e.	b_X/cow	Equation: $P_y = a + b \times$ b_X/cow $+ c \times$ b_SR $+ d \times$ d_SR *a*	*b*	*c*	*d*
Production per cow (kg)							
Milk yield	99	5.56	18.1	−13.16	0.35	0.82	−3.20
Fat yield	83	6.08	0.71	−16.03	9.79	1.98	−3.83
Protein yield	70	5.60	0.62	−10.40	9.46		−3.82
Lactose yield	43	4.33	0.93	10.24	−7.88	−1.42	−4.23
MS[b] yield	69	5.39	1.33	−10.86	5.35		−3.39
Fat content[c]	83	3.08	40.2	−2.60		1.32	−0.66
Protein content[c]	70	1.87	32.9	−2.44		0.46	−0.76
Lactose content[c]	43	1.10	46.6	0.61		−2.11	−0.29
Production per hectare (kg)							
Milk yield	99	9.36	18.1	8.39	0.504	−5.55	21.25
Fat yield	83	9.84	0.71	5.77	11.58	−3.93	20.29
Protein yield	70	9.84	0.62	24.68		−7.47	19.02
Lactose yield	43	6.21	0.93	22.67		−6.28	17.72
Milk solids yield	69	9.21	1.33	14.00	5.83	−6.54	20.15

b_X/cow = base production per cow; b_SR = base stocking rate; d_SR = change in stocking rate; P_y = percentage change; MS = milk solids.
$P_y = a + b \times$ b_X/cow $+ c \times$ b_SR $+ d \times$ d_SR, where a = origin, b = b_X/cow effect, c = b_SR effect and d = d_SR effect.
[a]Type I = common length experiments.
[b]MS = fat + protein.
[c]Values are expressed in g/kg.

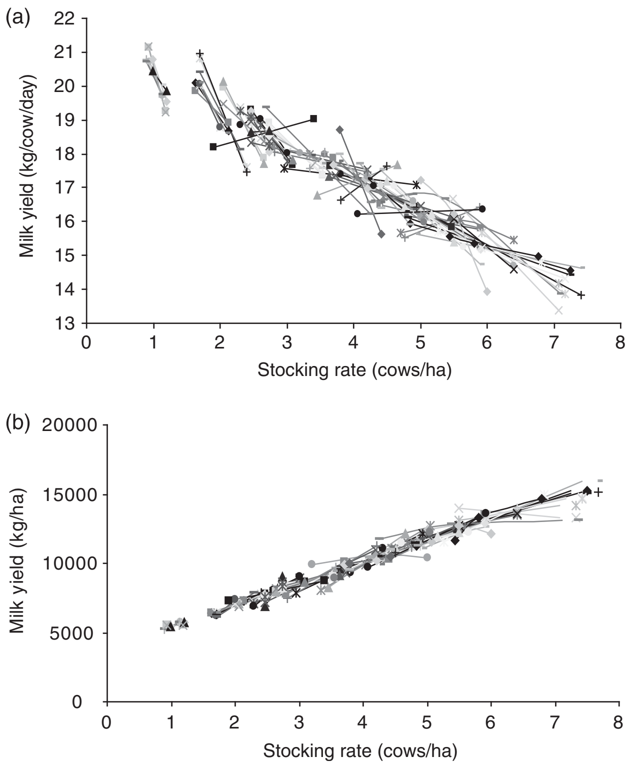

Figure 2 Visual representation of the response of (a) milk yield per cow per day and (b) milk yield per hectare (ha) to a stocking rate change within experiment for the Type I data set.

Type I and Type II data sets, respectively, suggests that the optimum SR per ha was not realised within the reviewed literature. This conclusion is further substantiated by the limited number of observations of reduced milk production per ha in response to an SR increase (Figure 2).

Although the results of this analysis illustrate that the response to an SR change in terms of milk yield per ha is similar for Type I and Type II data sets, the effects are not consistent for MS, fat, protein and lactose yield per ha. While MS yield per ha increased by 18.5% for Type I data, the increase within Type II data was only 11.4%. The comparatively reduced response in MS yield per ha within the Type II data (variable length experiments) is a consequence of a reduction in lactation length associated with increased SR within such experiments. While the reduction in lactation length within such studies has limited impact on milk yield per ha, the absence of late lactation milk, which is typically high in MS, considerably reduces the MS yield per ha associated with an increased SR. Type II data, despite the limited number of experimental observations, remain a truer reflection of the effect of an SR increase. Type I data contain experiments that are shorter and typically run during periods in which herbage supply is greatest, thereby biasing results in favour of increased SR as periods of gross underfeeding are ignored.

Previous studies have observed that as SR increases, milk production per cow declines due to reduced daily herbage allowance and intake associated with increased grazing severity (Le Du *et al.*, 1981), increased feed demand relative to animal requirements (Penno, 1999) and the inability of the animal to select greater quality herbage from within the sward. The same authors suggested that the favourable effects on milk production per ha with an increased SR are in part due to reduced herbage wastage (McMeekan, 1964), improved herbage growth and quality associated with increased grazing severity (Macdonald *et al.*, 2008) and increased energetic efficiency associated with reduced BW and body condition gain during lactation (McMeekan, 1964). This is in agreement with Hoden *et al.* (1991), who stated that the proportion of area refused in a paddock is lower at increased SRs, thus indicating greater herbage utilisation. At increased SRs, the density of the herbage is also slightly increased; therefore, there is an increase in the amount of herbage harvested, and energy intake per ha is increased (measured using the Net Energy system (UFL; Faverdin *et al.*, 2007) resulting in an increase in milk production per ha (Hoden *et al.*, 1991).

While the general effect of an SR increase is to reduce milk production per cow and increase milk production per ha, increased milk production per cow or reduced milk production per ha in response to an SR increase has occasionally been observed within the reviewed literature (as illustrated by the variability in response in Figure 2a and b). Penno (1999) considered SR as a continuum in terms of herbage availability and observed three distinct results to an SR change. First, at a low b_SR (and high herbage availability), milk production per cow and per ha increased as SR increased (Baker and Leaver, 1986; Michell and Fulkerson, 1987), as intake per cow was not compromised and the quality of available herbage was enhanced through increased grazing severity. Second, at a greater b_SR, an SR increase results in reduced herbage availability and consequently reduced milk production per cow, while milk production per ha increases due to greater herbage utilisation (Macdonald *et al.*, 2008). Finally, milk production per ha may be reduced in response to an SR increase, where herbage utilisation is high at the b_SR and further incremental SR increases result in similar herbage utilisation while increasing maintenance energy requirements per ha (McFeely *et al.*, 1975; Ahlborn and Bryant, 1992; Penno, 1999).

While the impact of a one cow/ha SR increase on milk production per ha is similar to Journet and Demarquilly (1979), the 10% reduction in milk production per cow reported in that study is considerably greater than the current findings (7.4% and 8.7% for Type I and Type II experiments, respectively). This difference in response to a one cow/ha SR change suggests that there is an interaction between the effect of SR and the cow characteristics within the two data sets. When the experiments used are sub-divided based on decade, mean daily milk and MS yield per cow has increased from the 1960s up to the 2000s ($P < 0.001$). In this period, the total increase in daily milk and MS yield was 10.13 and 0.96 kg/cow, respectively, equivalent to a mean increase of 1.8%, 1.6%, 3.2%, 0.8% and 2.9% per year for milk, fat, protein, lactose and MS yield per cow, respectively, from the 1960s to 2000s. Similarly, milk, fat, protein, lactose and MS yield per ha has increased by 1.8%, 1.6%, 1.7%, 1.0% and 1.4% per year, respectively, from 1960s to 2000s. This increase in productivity has been reported previously and is a consequence of increased emphasis of selection for milk production, including fat and protein yield, as milk yield has been the main objective criterion for selection in most temperate countries (Miglior *et al.*, 2005; Dillon *et al.*, 2006). The same authors have observed that the rate of increase in milk production per cow per year since 1985 has been 193, 131, 35 and 46 kg for the United States, The Netherlands, New Zealand and Ireland, respectively, while the rate of increase was 120 kg in France (L. Delaby, personal communication). This is equivalent to an increase of almost 2% of mean production per annum in the United States, The Netherlands and France, and approximately 1% of mean production in New Zealand and Ireland.

This analysis also shows that the milk production response per ha, to an SR increase, declines as b_SR increases (as the coefficients for b_SR are all negative). For example, with a mean milk yield per cow per day of 18 kg and an SR change of one cow/ha, the increase in milk yield per ha is 33.2%, where the b_SR is one cow/ha, and only 22.1% if the b_SR is three cows/ha. This result also explains why some experiments observe a reduction in milk production per ha in response to an SR increase. Similarly, the base milk production per cow significantly affects the response to an SR change. The results of this analysis show that the greater the base milk yield per cow per day, the lower the proportional reduction in milk production per cow and the greater the milk production response per ha.

The predicted effect of an SR change on the proportional reduction in milk production per cow is not precise within the current analysis as evidenced by the high residual error term as well as the variability in response to an SR change (Figure 2a). The difficulty in prediction relates to the definition of SR used within traditional SR experiments and specifically in relation to the effect of an SR change on the availability of feed to each individual animal. An SR increase results in a greater energy demand within the production system and the proportional effect on production per cow is dependent on the change in energy status of animals within the system.

The energy supply within the b_SR treatments of each experiment was estimated (according to the energy requirements for maintenance and production using the net energy system (Faverdin *et al.*, 2007)) and divided by the increased SR to reflect the reduction in energy status of each cow within an increased SR treatment. The mean energy available per cow per day was reduced by 2.5 UFL according to a one cow/ha SR increase, and according to Faverdin *et al.* (2007), this should have resulted in a 5.0-kg reduction in milk yield per cow per day. As actual milk yield declined only by 1.1 kg, herbage utilisation may have increased to achieve greater than anticipated production. The actual reduction in milk production observed (1.1 kg milk/2.5 UFL = 0.44 kg) is similar to that associated with a 1-kg reduction in daily herbage allowance (Peyraud *et al.*, 2001). While it is widely acknowledged that milk production from pasture is dependent on numerous environmental, plant, animal and management factors controlling herbage intake and rumen digestion (Dillon, 2006), the results of this analysis illustrate that as SR increases by one cow/ha, the net energetic consequences are akin to a reduction of 1 kg in daily herbage allowance per cow.

Holmes *et al.* (2002) suggested that cows per ha is increasingly misleading as a measure of the balance between feed demand and supply, although cows per ha is still widely used. Other authors such as Macdonald *et al.* (2008) have suggested that alternative definitions of SR, such as comparative SR, be developed as cow BW/ton of feed offered. The low predictability of proportional change in milk production per cow according to the classical SR definition of cows per ha suggests that SR may be more appropriately defined in future experiments in terms of the change in available feed or energy offered per animal within each treatment. In addition, the change in the slope of milk production variables per cow and per ha when viewed in terms of BW/ha requires that increased information on the nature of the animal used be supplied in future SR experiments.

Conclusion

The results illustrate that while production per cow is reduced, a strong positive relationship exists between SR and milk production per ha. The results also indicate that the reduction in milk production per cow associated with an SR increase is a consequence of both an increased intensity of grazing associated with a reduction in daily herbage allowance and a reduction in lactation length. The low predictability of proportional change in milk production per cow, according to the classical SR definition of cows per ha over a defined period, suggests that SR may be more appropriately defined in terms of the change in available feed or energy offered per animal within each treatment rather than cows per ha.

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