Evaluation of Different Energy Feeding Systems With Production Data from Lactating Dairy Cows Offered Grass Silage-Based Diets

T. Yan,* R. E. Agnew,*† J. J. Murphy,‡ C. P. Ferris,* and F. J. Gordon*†

*The Agricultural Research Institute of Northern Ireland, Hillsborough, Co Down, BT26 6DR

†Department of Agricultural and Rural Development, Northern Ireland, and The Queen's University of Belfast, BT9 5PX

‡Teagasc, Moorepark Research Centre, Fermoy, Co. Cork, Irish Republic

ABSTRACT

A set of data from 838 lactating dairy cows, drawn from 12 long-term feeding studies (at least 8 wk/period), was used to evaluate the energy feeding systems for dairy cows currently adopted in Australia, France, The Netherlands, the United Kingdom, and the United States. The animals were offered mixed diets of concentrates, forage [grass silages ($n = 33$) and corn silages ($n = 5$)] ad libitum. Data used in the present evaluation were either measured [dry matter (DM) intake, milk production and live weight], measured/estimated [dietary metabolizable energy (ME) concentration] or estimated [milk energy output and live weight change (LWC)]. The mean-square prediction error (MSPE) was used for the evaluation. Total ME intake, milk yields, and LWC varied from 91 to 338 MJ/d, 7.7 to 48.9, and -1.23 to 1.73 kg/d, respectively. Australian and French systems predicted total energy requirement and milk yield relatively well, while British, Dutch and American systems underpredicted total energy requirement by proportionately 0.06, 0.04, and 0.03, respectively; and overpredicted milk yield by 0.09, 0.06, and 0.04. The Agricultural and Food Research Council (AFRC) each produced a relatively larger error of the bias (predicted – actual data) over the total MSPE for ME requirement and milk yield and a relatively smaller error of random than other systems. However, an addition of proportionately 0.05 to the total predicted ME requirement of AFRC, as suggested in this system and currently used in the UK, indicated the prediction accuracy of ME requirement and milk yield is similar to Australian and French systems. Nevertheless, all the systems had a poor prediction of LWC. For each system, the total prediction error (total MSPE) was mainly derived from the line (slope; 0.49 to 0.64 of total MSPE), while less derived from the random (0.20 to 0.48 of total MSPE),

indicating a large variation between the predicted and actual LWC existed among individual cows. The residual plots of the residual differences in LWC against predicted LWC revealed that the prediction error was greater with increasing LWC. It is concluded that Australian and French systems have a better prediction of total energy requirement and milk yield than other systems, and LWC is an inappropriate indicator of energy balance in lactating dairy cows.

(Key words: dairy cow, energy feeding system, energy requirement, prediction)

Abbreviation key: DOMD = digestible OM in total DM, E_g = energy balance or energy for live weight change, E_l = milk energy output, $E_{l(0)}$ = milk energy output adjusted to zero energy balance, k_g = efficiency of utilization of metabolizable energy for live weight gain, k_l = efficiency of utilization of metabolizable energy for lactation, k_t = efficiency of utilization of mobilized tissue energy for lactation, LWC = live weight change, ME_m = metabolizable energy requirement for maintenance, NE_m = net energy requirement for maintenance.

INTRODUCTION

Energy feeding systems for dairy cows currently adopted in Europe [Van Es, 1978; Institut National De la Recherche Agronomique (INRA), 1989; Agricultural and Food Research Council (AFRC), 1993] and North America [National Research Council (NRC), 2001] were developed from calorimetric data published over 30 yr ago. In practice, these systems are applied directly to lactating dairy cows, although an activity allowance is added to the maintenance energy requirement in some systems to account for normal voluntary activity of cows that would be housed in free-stall systems (INRA, 1989; AFRC, 1993; NRC, 2001). However, a number of recent calorimetric studies reported by Agnew and Yan (2000) have demonstrated that the maintenance energy requirement recommended in these systems was lower than that for current dairy cows. One reason for may

Received July 30, 2002.

Accepted November 26, 2002.

Corresponding author: T. Yan; e-mail: tianhai.yan@dardni.gov.uk.

be the improvement of the cow genetic merit, which can increase the maintenance metabolic rate of dairy cows (Agnew and Yan, 2000). For example, Yan et al. (1997b) reported a fasting heat production of 0.45 MJ/kg^{0.75} in nonpregnant and nonlactating dairy cows, a value that is proportionately over 0.3 higher than those proposed in these energy feeding systems. The underprediction of maintenance energy requirements may restrict the production potential of dairy cows when using these systems to formulate diets for cows managed under practical farm conditions.

The AFRC (1990) used production study data from three UK research centers to test the metabolizable energy (ME) system of Agricultural Research Council (ARC; 1980) and reported that the milk yields were either overpredicted by proportionately 0.12 and 0.05 or underpredicted by 0.12 with the three sets of data. A recent study also reported that milk energy output was underpredicted by proportionately 0.08 when the production data of lactating dairy cows were used to test the net energy (NE) system used in Switzerland (derived from Van Es, 1978; Schwager-Suter et al., 2001). However, the dietary energy concentrations in some cows of AFRC (1990) and in all cows of Schwager-Suter et al. (2001) were calculated from the tabulated values, and this could influence the accuracy of evaluation.

Since 1992, a number of feeding experiments with lactating dairy cows (Holstein/Friesian) were conducted at the Agricultural Research Institute of Northern Ireland (ARINI) and Moorepark Research Center in Southern Ireland (Moorepark). All of the animals in these experiments were on treatment for at least 8 wk and the ME concentrations of the total diets were either measured directly in digestibility trials and calorimetry or predicted from the *in vivo* digestible OM in total DM (DOMD). The objective of the present study was to use these data to evaluate a number of energy feeding systems currently adopted in Europe [Van Es, 1978; INRA, 1989; AFRC, 1990 and 1993], Australia (Standing Committee on Agriculture-SCA, 1990) and North America (NRC, 2001)]. The evaluation was carried out in three areas: total energy intake, milk yield, and live weight change (LWC).

MATERIALS AND METHODS

The energy feeding systems selected in the present study included the ME systems currently used in Australia (SCA, 1990), the UK (AFRC, 1990 and 1993), and the NE systems adopted in The Netherlands (Van Es, 1978), France (INRA, 1989), and the USA (NRC, 2001). The differences between AFRC (1990) and (1993) are that the latter increases the activity allowance from

0.0091 to 0.0095 of live weight (MJ/d) and reduces the energy content per unit of LWC from 23.4 to 19.0 MJ/kg of full live weight. In practice, AFRC (1993) adopts a safety margin of proportionately 0.05 to the total ME requirement and this will be referred as AFRC (1993, +0.05). The principle for the present evaluation is that total energy requirement is a sum of energy required for maintenance, milk production, LWC, and pregnancy.

Animals and Feed

Data from 838 lactating cows (Holstein/Friesian), drawn from 12 long-term feeding experiments (period length ≥ 8 wk), were used in the present evaluation. Seven trials were conducted at ARINI [Patterson et al., 1996; Keady and Mayne, 1998; Yan et al., 1998 and 2002; Ferris et al., 1999a; Keady et al., 1999; C. P. Ferris, 2000 (personal communication)] and five trials at Moorepark (Fitzgerald et al., 1994; Keady and Murphy, 1996 and 1997; O'Mara et al., 1998; Fitzgerald and Murphy, 1999). The animals used in these trials represented a range of genetic merits and lactation numbers (from 1 to 9). The mean, minimum and maximum values, and standard deviation for live weight, milk yield, milk composition, DM intake, and dietary ME concentration, are presented in Table 1.

All experiments involved *ad libitum* feeding of mixed diets of perennial ryegrass silages ($n = 33$) and concentrates, with the exception of three studies (Fitzgerald et al., 1994; O'Mara et al., 1998; Fitzgerald and Murphy, 1999) in which corn silages ($n = 5$) were used to replace a part of grass silages. The concentrates used in these experiments were based on cereal grains (barley, wheat, and corn), by-products (corn gluten meal, sugar beet pulp, and citrus pulp), protein supplements (fish meal, soyabean meal, and rapeseed meal) and a mineral/vitamin supplement (Table 2).

Calculation of Energy Intake and Milk Energy Output

Total gross energy (GE) intake and energy outputs from feces and urine were measured in digestibility trials, and methane was determined in calorimetric chambers in the experiments of Patterson et al. (1996), Keady and Mayne (1998), Yan et al. (1998 and 2002), Ferris et al., (1999a), and C. P. Ferris (2000, personal communication). Dietary ME concentration was calculated as the difference between GE intake and energy outputs from feces and urine and as methane. Studies of dietary ME concentration by Ferris et al. (1999a) and Patterson et al. (1996) were separately reported by Ferris et al. (1999b) and Yan et al. (1996), respectively. In the studies by Fitzgerald et al. (1994), Keady and

Table 1. The live weight, intake, and milk production data of individual dairy cows (n = 838) obtained in 12 long feeding studies used in the present evaluation.

	Mean	s.d.	Minimum	Maximum
Live weight (kg)	550	65.5	388	775
Live weight change (kg/d)	0.23	0.406	-1.23	1.73
DMI (kg/d)	16.7	2.91	8.2	26.9
Forage proportion (kg/kg DM)	0.598	0.1206	0.298	0.869
Milk yield (kg/d)	23.8	6.88	7.7	48.9
Milk fat (g/kg)	42.0	5.93	21.7	69.4
Milk protein (g/kg)	32.9	2.96	16.2	42.9
Milk lactose (g/kg)	48.4	2.28	42.6	54.4
ME concentration (MJ/kg DM)	11.5	0.57	10.3	12.6
ME/GE	0.636	0.0297	0.573	0.688
ME intake (MJ/d)	192.6	38.48	90.9	338.0
Milk energy output (MJ/d)	75.7	21.51	28.9	161.4

Murphy (1996 and 1997), O'Mara et al. (1998), Fitzgerald and Murphy (1999) and Keady et al. (1999), dietary ME concentration (MJ/kg DM) was estimated using in vivo DOMD [$0.016 \times \text{DOMD (g/kg)}$] (AFRC, 1993). It was then adjusted for the effect of dietary forage proportion on methane production, because the latter two parameters are positively related as reported by Yan et al. (2000). In the experiment by Keady et al. (1999), two concentrate supplements contained a small amount of rumen-protected fat (Table 2), and the ME concentrations in the mixed diets with these two supplements, predicted from in vivo DOMD and then adjusted for dietary forage proportion, were further adjusted for the additional energy contributed from the added fat.

All cows used in the digestibility measurements in the experiments included in the present study were offered experimental diets for at least 3 wk before a 6-d total collection of feces and urine. The details of the procedure of these measurements are as described by Mayne and Gordon (1984) for the ARINI experiments and by Keady et al. (1996) for the Moorepark trials.

Milk energy output (E_l ; MJ/d) was estimated from the equation of Tyrrell and Reid (1965) based on milk yield and milk concentrations of fat, protein, and lactose [equation (1)].

$$E_l = \text{MY} \times (0.0384 \text{ fat} + 0.0223 \text{ protein} + 0.0199 \text{ lactose} - 0.108) \quad (1)$$

where MY is milk yield (kg/d); fat, protein, and lactose represent, respectively, their concentrations in milk (g/kg).

Calculation of Live Weight Change and Energy for Live Weight Change

Live weights of cows were recorded weekly in the experiments included in the present study. The calculation of LWC was a key factor for the accuracy of the

present evaluation. A number of approaches were taken to minimize the error that could arise in the calculation, which were as follows: 1) the data used excluded those obtained before wk 3 of lactation; 2) all data used were obtained for feeding periods between 8 and 10 wk. For continuous design experiments, the length of experimental period was divided into early, mid, and late stages of lactation, and each stage was for a period of 8 to 10 wk; 3) if the data for a cow (e.g., live weight, intake, milk production) varied greatly between a few weeks due to the unexpected factors (e.g., illness), this cow's data were not included in the present study; 4) the LWC data used were all derived from significant relationship (linear; $P < 0.05$) between live weights and recording date. If the relationship was not significant, cow data were not used in the present study.

There were no extreme diets offered, and all cows were fed ad libitum in all experiments included in the present study. Therefore, within a period of 8 to 10 wk, the live weights of a cow did not normally have a great variation.

LWC (kg/d) was calculated in the present study using linear [equation (2)] and quadratic [equation (3)] regressions of weekly live weights (LW; kg) against recording date (days on treatments, Days).

$$\text{LW} = a [\text{Days}] + b \quad (2)$$

$$\text{LW} = a [\text{Days}]^2 + b [\text{Days}] + c \quad (3)$$

LWC was taken as 'a' value in equation (2). In equation (3), average LWC was estimated using equation (3a),

$$\text{LWC} = 2a * \overline{\text{Days}} + b \quad (3a)$$

where $\overline{\text{Days}} = \Sigma(0*7 + 1*7 + 2*7 + \dots + i*7/i)$, i = number of weeks on treatments (0, 1, 2, ..., up to 10).

The LWC obtained in linear equation (2) is the same as the average LWC calculated from equation (3a) in the quadratic regression.

Table 2. The ingredient composition of concentrates used in the experiments included in the present study (g/kg DM).

	Barley	Maize	Wheat	Maize gluten	MSBP ¹	Sugar beet pulp	Citrus pulp	Soyabean meal	Rapeseed meal	Fish meal	Molassses	Fat ²	M/V ³
Fitzgerald et al. (1994)	135					435		400					30
Keady and Murphy (1996)	375					400		123		75			27
Patterson et al. (1996)	702							245			26		27
Keady and Murphy (1997)	375					400		123		75			27
Keady and Mayne (1998)	1				527		101	229	61		26	28	28
	2	157	389	145				192	63		26		28
O'Mara et al. (1998)	1	369				435		169					27
	2	264				434		275					27
	3	134				431		406					29
	4					427		542					31
Yan et al. (1998)		183	186		381			175		53			22
Ferris et al. (1999a)		176	176		360			212		51			25
Fitzgerald and Murphy (1999)		135				435		400					30
Keady et al. (1999)	1	160	179	346				243	13		26		33
	2				495		85	290	50		26	14	40
	3	96		375	179			91	204		26		29
	4				51	501	92	78	203		26	22	27
Yan et al. (2002)		221	216			297		241					25
C. Ferris (Pers. Comm.)		135	308	142		128		235			25		27

¹Molassed sugar beet pulp.²Rumen protected fat.³Minerals and vitamins supplement.

The energy retained in or mobilized from body tissue (E_g , MJ/d) was then calculated as LWC multiplied by the energy content per unit of LWC, as suggested in the above energy feeding systems.

Prediction of Total Energy Requirement

ME systems. Actual ME intake (ME_{int}) was calculated as total DM intake multiplied by dietary ME concentration. The ME requirement for pregnancy for late pregnant cows was estimated and then subtracted from ME_{int} . Total ME requirement (ME_{req} ; MJ/d) was predicted as a sum of ME requirement for maintenance (ME_m), lactation (ME_l), and LWC (ME_g ; MJ/d; AFRC, 1990 and 1993; SCA, 1990):

$$ME_{req} = ME_m + ME_l + ME_g \quad (4)$$

$$= NE_m/k_m + E_l/k_l + E_g/k_g \quad \text{If } E_g > 0 \quad (5)$$

$$= NE_m/k_m + E_l/k_l + 0.84 E_g/k_g \quad \text{If } E_g < 0, \quad (6)$$

where NE_m is the NE requirement for maintenance; k_m , k_l , or k_g is the efficiency of ME use for maintenance, lactation, or LWC. The k_m or $k_l = ME/GE \times 0.35 + 0.503$ or 0.42 (AFRC, 1990 and 1993). The $k_g = 0.95 k_l$ (AFRC, 1990 and 1993) or 0.60 (SCA, 1990).

NE systems. In the NE feeding systems, k_m is assumed to be equal to k_l , and then actual intake of NE for lactation (NEL , NEL_{int} , MJ/d) was calculated as equation (7; Van Es, 1978; INRA, 1989) or equation (8; NRC, 2001). The NEL requirement for pregnancy for late pregnant cows was calculated and then subtracted from NEL_{int} :

$$NEL_{int} = ME_{int} \times (0.24 \times ME/GE + 0.463) \quad (7)$$

$$= DMI \times (0.703 \times ME_{con} - 0.795), \quad (8)$$

where DMI is DM intake (kg/d), and ME_{con} is dietary ME concentration (MJ/kg DM).

Total NEL requirement (NEL_{req}) was predicted as a sum of NE_m , E_l , and E_g [equation (9)]:

$$NEL_{req} = NE_m + E_l + a \times E_g \quad (9)$$

where a is equal to 1 (Van Es, 1978; INRA, 1989) or 0.64/0.75 (NRC, 2001) for positive LWC, or 0.80 (Van Es, 1978; INRA, 1989) or 0.82 (NRC, 2001) for negative LWC.

Prediction of Milk Yield and Live Weight Change

Milk yield (kg/d) was predicted as total predicted E_l (MJ/d) divided by energy concentration in milk. For the ME system, the predicted E_l was calculated as ME_l (estimated as the difference between ME_{int} and ME_m

and ME_g) multiplied by k_l (AFRC, 1990 and 1993; SCA, 1990), while for the NE system, the predicted E_l was calculated as the difference between NEL_{int} and NE_m and NE_g (Van Es, 1978; INRA, 1989; NRC, 2001).

Similarly, the LWC (kg/d) of full live weight was predicted as total predicted E_g (MJ/d) divided by energy content per unit of LWC, as suggested in each of the above systems. For the ME system, the predicted E_g was calculated as ME_g (estimated as the difference between ME_{int} and ME_m and ME_l) multiplied by k_g (AFRC, 1990 and 1993; SCA, 1990), while for the NE system, the predicted E_g was calculated as the difference between NEL_{int} and NE_m and NE_l (Van Es, 1978; INRA, 1989; NRC, 2001).

Evaluation of Energy Intake, Milk Yield, and Live Weight Change

The prediction accuracy was examined using the mean-square prediction error (MSPE) as described by Rook et al. (1990). The MSPE is defined as equation (10) and can be regarded as the sum of three components in equation (11):

$$MSPE = \frac{1}{n} \sum (P - A)^2 \quad (10)$$

$$MSPE = (\bar{P} - \bar{A})^2 + S_P^2(1 - b)^2 + S_A^2(1 - r^2), \quad (11)$$

where P or A is predicted or actual energy intake (energy requirement), milk yield, or LWC; n is the number of pairs of values of P and A compared ($n = 838$); $\bar{P}$ or $\bar{A}$ are the means of P or A ; S_P^2 or S_A^2 are the variances of P or A ; b and r are, respectively, the slope and correlation coefficients of the linear regression of P on A . The three components are, thus, due to mean bias ($\bar{P} - \bar{A}$), line bias (the deviation of the slope), and random variation of the slope. In order to compare the accuracy of prediction of energy requirement between ME and NE systems, the MSPE is expressed as the mean prediction error ($MPE = \sqrt{MSPE/\bar{A}}$).

Residual plots were also used to evaluate if there was an effect of energy intake, milk yield, or LWC on the prediction accuracy. The plots were graphed using the predicted energy requirement, predicted milk yield, or predicted LWC (x-axis) against the corresponding difference (y-axis) between predicted data and actual data of energy intake, milk yield, or LWC.

RESULTS

Diets and Animal

The quality of grass silages ($n = 33$) used in the trials used in the present study varied widely. The mean val-

Table 3. The accuracy of prediction of energy requirement from different energy feeding systems using the model of Mean-Square Prediction Error and the data of lactating dairy cows ($n = 838$) obtained in 12 long term feeding studies.

	Energy intake (MJ/d)					Proportion of MSPE			
	Predicted	Actual	Bias ¹	Proportion ²	s.e.	MPE	Bias	Line	Random
ME systems (ME)									
AFRC (1990)	181	192	-10.8	-0.056	22.4	0.13	0.18	0.09	0.73
AFRC (1993)	180	192	-12.2	-0.063	21.1	0.13	0.23	0.06	0.71
AFRC (1993, +0.05)	189	192	-3.2	-0.017	22.2	0.12	0.02	0.12	0.86
SCA (1990)	193	192	1.2	0.006	21.8	0.11	0.00	0.17	0.83
NE systems (NEL)									
Van Es (1978)	114	118	-4.4	-0.037	13.7	0.12	0.09	0.11	0.80
INRA (1989)	119	118	0.3	0.003	14.9	0.13	0.00	0.19	0.81
NRC (2001)	119	122	-3.2	-0.026	13.9	0.12	0.05	0.12	0.84

¹Predicted ME (NE_L) requirement – Actual ME (NEL) intake.

²(Predicted ME (NE_L) requirement – Actual ME (NE_L) intake)/Actual ME (NE_L) intake.

ues for these silages were: pH, 4.0 (s.d. 0.41); ammonia-nitrogen/total-nitrogen, 111 (s.d. 75.4) g/kg; DM, 236 (s.d. 56.2) g/kg; GE, 18.4 (s.d. 0.66) MJ/kg DM; crude protein, 150 (s.d. 25.8) g/kg DM; neutral detergent fiber, 557 (s.d. 73.6) g/kg DM; ash, 87 (s.d. 11.9) g/kg DM. The corn silages ($n = 5$) used contained a mean pH, ammonia-nitrogen/total-nitrogen, DM (g/kg), and crude protein, neutral detergent fiber and ash (g/kg DM) of 3.9 (s.d. 0.07), 33 (s.d. 15.1), 267 (s.d. 40.4), 103 (s.d. 16.0), 546 (s.d. 29.5), and 64 (s.d. 2.0), respectively.

There was a large range in live weight (388 to 775 kg), milk yield (7.7 to 48.9 kg/d), and forage proportion of the diets offered (0.30 to 0.87; Table 1). Consequently, total DM intake ranged from 8.2 to 26.9 kg/d, and total ME intake ranged from 91 to 338 MJ/d. LWC data calculated from linear regression of live weights against recording date were similar to those estimated from quadratic regression. Mean LWC was 0.23 (s.d. 0.406) kg/d with a range from -1.23 to 1.73 kg/d. A total of 225 cows exhibited negative LWC, while the remaining 613 cows had positive LWC.

Energy Requirement Predictions

The results of evaluation of total ME (NEL) intake using MSPE are presented in Table 3. With the exception of INRA (1989) and SCA (1990), all systems underpredicted energy requirements, expressed as the difference between predicted energy requirement and actual energy intake (bias). The underprediction was proportionately 0.06 with AFRC (1990 and 1993), 0.04 with Van Es (1978), and 0.03 with NRC (2001). SCA (1990) and INRA (1989) marginally overpredicted the total energy requirement. The MPE was slightly lower with SCA (1990) than other systems. Although AFRC (1990 and 1993) produced a low error derived from the line over total MSPE, the error derived from the bias was considerably large in comparison to the other systems.

The error derived from the random was, thus, lower with AFRC (1990 and 1993). However, when a safety margin of proportionately 0.05 was added to the total ME requirement predicted from AFRC (1993), as suggested in this system and currently used in the UK, the prediction accuracy of AFRC (1993, +0.05) was similar to INRA (1989) and SCA (1990).

The residual plots between predicted energy requirement minus actual energy intake and predicted energy requirement are presented in Figures 1a and 1b. The residual plots of AFRC (1993) were similar to AFRC (1990); therefore, the former was omitted in Figure 1a. The majority of residual plots for AFRC (1990), Van Es (1978), and NRC (2001) was below zero (underpredicted), while the plots for AFRC (1993, +0.05), SCA (1990), and INRA (1989) were distributed around zero. The standard deviation values for the residual differences (predicted energy requirement – actual energy intake) were similar within ME systems [23.1, 22.1, 22.7, and 21.9 for AFRC (1990), AFRC (1993), AFRC (1993, +0.05), and SCA (1990), respectively] or within NE systems [14.0, 15.0, and 14.2 for Van Es (1978), INRA (1989) and NRC (2001), respectively].

Milk Yield Predictions

The MSPE evaluation of milk yield is presented in Table 4. In accordance with the prediction of ME requirement, AFRC (1990 and 1993), Van Es (1978), and NRC (2001) overpredicted milk yield by over 2.0, 1.4, and 1.0 kg/d (or proportionately 0.09, 0.06, and 0.04), respectively. The AFRC (1990 and 1993) had a marginally greater MPE and a considerably larger error derived from bias as a proportion of MSPE than other systems. The SCA (1990) had a greater proportion of error derived from random than other systems, while this value was considerably lower with AFRC (1990 and 1993). However, an addition of a safety margin of

Figure 1. a) Relationship between residual metabolizable energy (ME) intake (predicted ME requirement – actual ME intake) and predicted ME requirement from different energy feeding systems using production data ($n = 838$) of lactating dairy cows. b) Relationship between residual NE_L intake (predicted NE_L requirement – actual NE_L intake) and predicted NE_L requirement from different energy feeding systems using production data ($n = 838$) of lactating dairy cows.

Table 4. The accuracy of prediction of milk yield from different energy feeding systems using the model of Mean-Square Prediction Error and the data of dairy cows (n = 838) obtained in 12 long term feeding studies.

Systems	Milk yield (kg/d)					Proportion of MSPE			
	Predicted	Actual	Bias ¹	Proportion ²	s.e.	MPE	Bias	Line	Random
AFRC (1990)	26.0	23.8	2.2	0.092	4.57	0.22	0.17	0.14	0.69
AFRC (1993)	26.2		2.4	0.100	4.40	0.21	0.22	0.13	0.65
AFRC (1993, +0.05)	24.4		0.6	0.025	4.22	0.19	0.02	0.11	0.87
SCA (1990)	23.5		-0.3	-0.013	4.15	0.19	0.00	0.08	0.92
Van Es (1978)	25.2		1.4	0.059	4.22	0.19	0.08	0.10	0.82
INRA (1989)	23.6		-0.2	-0.008	4.47	0.20	0.00	0.12	0.88
NRC (2001)	24.8		1.0	0.042	4.29	0.19	0.04	0.12	0.84

¹Predicted milk yield – Actual milk yield.²(Predicted milk yield – Actual milk yield)/Actual milk yield.

proportionately 0.05 to the predicted ME requirement of AFRC (AFRC, 1993 + 0.05) improved the prediction accuracy of milk yield to be similar to other systems in terms of MPE and error derived from random variation.

The parallel model was used to determine whether there was any significant difference between the systems in coefficients or constants of linear regression of predicted against actual milk yield. Because SCA (1990) produced a better prediction than other systems, milk yields predicted by this system were used to compare to those predicted by other systems. The model used was: $y = a + b \cdot x + x \cdot \text{systems} + \text{systems}$, where y , x , and systems represent, respectively, actual milk yields, predicted milk yields, and energy feeding systems. The coefficients were 0.73, 0.75, 0.79, 0.81, 0.79, 0.76, and 0.78, respectively, for AFRC (1990), AFRC (1993), AFRC (1993, +0.05), SCA (1990), Van Es (1978), INRA (1989), and NRC (2001); and the constants were 4.8, 4.2, 4.7, 4.8, 4.0, 5.9, and 4.6 kg/d, respectively. There were no significant differences in constants between SCA (1990) and other systems. The coefficient for SCA (1990) was also similar to those of Van Es (1978), INRA (1989), AFRC (1993, +0.05), and NRC (2001), while significantly greater than those of AFRC (1990 and 1993).

The residual plots for milk yield, expressed as the difference between predicted and actual milk yield against predicted milk yield, are presented in Figure 2. Since the results were similar between AFRC (1990) and AFRC (1993), the plots for AFRC (1993) were not presented. In accordance with the prediction of total energy requirement, the majority of residual plots for AFRC (1990), Van Es (1978), and NRC (2001) was above zero (overpredicted). The residual plots were distributed around zero for AFRC (1993, +0.05), SCA (1990), and INRA (1989). The standard deviation values for the residual differences (predicted – actual milk yield) were similar for these systems and were 4.7, 4.5, 4.4, 4.5, 4.4, 4.7, and 4.5 for AFRC (1990), AFRC (1993), AFRC (1993, +0.05), SCA (1990), Van Es (1978), INRA (1989), and NRC (2001), respectively.

Live Weight Change Predictions

The evaluation of LWC with MSPE is presented in Table 5. Although the mean predicted LWC was the same as the mean actual LWC with SCA (1990) and INRA (1989), SE and MPE values for all systems were substantially large. The random error as a proportion of MSPE was <0.5 for all systems. The error derived from the line (slope) with all systems was between 0.49 to 0.64 of total MSPE, indicating a large variation between the predicted and actual LWC existed among individual cows.

The residual plots of the differences between predicted minus actual LWC against predicted LWC for all systems are presented in Figure 3, except for AFRC (1993), because the plots for this system were similar to those of AFRC (1990). For all systems, there was a positive and significant ($P < 0.001$) relationship between residual LWC (predicted – actual LWC), and predicted LWC and the values of square of correlation coefficient (r^2) ranged from 0.52 (INRA, 1989) to 0.70 (AFRC, 1993, +0.05). These relationships indicate that the prediction error for each system is greater with increasing LWC. The standard deviation values for the residual LWC were relatively large for all systems and were 0.64, 0.75, 0.72, 0.66, 0.68, 0.57, and 0.60 for AFRC (1990), AFRC (1993), AFRC (1993, +0.05), SCA (1990), Van Es (1978), INRA (1989), and NRC (2001), respectively.

DISCUSSION

Accuracy of Calculation of Data

The primary objective of the present study was to use the production data of lactating dairy cows to evaluate energy feeding systems currently used in a number of countries. The evaluation involved calculations of total DM intake, dietary ME concentration, milk production, milk energy output, live weight, and LWC. The DMI, milk production, and live weight can be accurately recorded in a well-controlled experiment. A key aspect

Figure 2. Relationship between residual milk yield (predicted – actual) and predicted milk yield from different energy feeding systems using production data ($n = 838$) of dairy cows.

Table 5. The accuracy of prediction of live weight change (LWC) from different energy feeding systems using the model of Mean-Square Prediction Error and the data of lactating dairy cows (n = 838) obtained in 12 long term feeding studies.

Systems	Live weight change (kg/d)					Proportion of MSPE			
	Predicted	Actual	Bias ¹	Proportion ²	s.e.	MPE	Bias	Line	Random
AFRC (1990)	0.55	0.23	0.32	1.391	0.582	3.14	0.21	0.49	0.30
AFRC (1993)	0.67		0.44	1.913	0.716	3.83	0.26	0.54	0.20
AFRC (1993, +0.05)	0.64		0.41	1.783	0.682	3.64	0.25	0.53	0.22
SCA (1990)	0.23		0.00	-0.004	0.602	2.92	0.00	0.64	0.36
Van Es (1978)	0.45		0.22	0.957	0.624	3.14	0.10	0.59	0.31
INRA (1989)	0.23		0.00	0.004	0.485	2.50	0.00	0.52	0.48
NRC (2001)	0.32		0.09	0.391	0.523	2.65	0.02	0.55	0.43

¹Predicted LWC – Actual LWC.

²(Predicted LWC – Actual LWC)/Actual LWC.

of the present evaluation is, therefore, the accuracy of calculation of dietary ME concentration and LWC. The ME concentrations in the total diets in the present study were either measured directly via digestibility trials and calorimetry or estimated from the in vivo DOMD when cows were offered the total diets ad libitum. All cows used for digestibility measurements were offered experimental diets for at least 3 wk before the commencement of digestibility trials. The feces and urine were separately collected for a total of 6 d. The procedure used is, thus, a normal approach as adopted elsewhere.

The dietary ME concentrations (MJ/kg DM) in some experiments included in the present evaluation were calculated from DOMD (g/kg) using a factor of 0.016 (AFRC, 1993). This was then adjusted for the effect of dietary forage proportion for methane production (Yan et al, 2000) and in Keady et al. (1999), and was further adjusted for the effect of a small addition of fat in the concentrates. The factor of 0.016 of AFRC (1993) is the same as that reported by Givens et al. (1989) in 124 grass silages, and close to that (0.0157) obtained recently with 171 grass silages using linear regression of silage ME concentrations against DOMD data (Agnew and Yan, 2002).

As stated previously in the Materials and Methods section, a number of approaches were adopted in the present study to minimize the error that could arise in the calculation of LWC. This would result in a relatively accurate estimation of LWC using regression techniques in feeding studies. Indeed, the LWC obtained in the present study using both linear and quadratic regression of live weight against recording date were similar.

All experiments included in the present study were designed to evaluate the effects of animal factors (e.g., cow genetic merit and breed of cows) and/or dietary factors (e.g., silage DM concentration, silage additive, forage proportion, forage type, and concentrate type).

These factors normally exist in the commercial farms across the world. All diets used were formulated according to AFRC energy and protein feeding systems (AFRC, 1993). Although Keady et al. (1999) investigated the effect of two levels of undegradable CP in concentrates, the total CP levels in the concentrates were only around 220 g/kg DM, and the degradable CP in total diets were formulated to meet the requirement of the micro-organism activity in the rumen (AFRC, 1993). Therefore, there were no extreme diets offered in the experiments included in the present study. This would exclude the adverse effects of dietary factors on animals' health and enhance the accuracy of the present evaluation.

In the present study, all intake, milk production, and live weight data were obtained from feeding trials involving period length of ≥ 8 wk and the dietary ME concentrations were measured or estimated from the in vivo DOMD. These would minimize the bias of variation which may arise during short periods and the error that normally occurs in production data, in which the tabulated ME values are used for concentrate ingredients and ME concentration of a mixed diet is calculated, assuming no associative effect between concentrates and forage. The dietary ME concentration obtained from ad libitum feeding in the present study also avoids the inaccuracy that may arise from the correction of feeding levels when the dietary ME concentration is measured or estimated at the maintenance feeding.

Prediction of Total ME (NE_L) Requirement and Milk Production

In a review of calorimetric studies of lactating dairy cows published since 1976, Agnew and Yan (2000) reported that AFRC (1990) and Van Es (1978) underpredicted total energy requirement by proportionately 0.06 and 0.04, respectively, while AFRC (1993, +0.05), SCA (1990), and NRC (2001) performed well. The same de-

Figure 3. Relationship between residual live weight change (LWC) (predicted – actual LWC) and predicted LWC from different energy feeding systems using production data (n = 838) of lactating dairy cows.

degrees of underprediction with the former two systems are also found in the present evaluation using production data. The AFRC (1993, +0.05), SCA (1990), and INRA (1989) predicted a mean ME (NEL) requirement that was similar to the mean actual ME (NEL) intake in the present study. Accordingly, in the present study, milk yield was overpredicted by proportionately 0.10, 0.09, 0.05, and 0.04 with AFRC (1993), AFRC (1990), Van Es (1978), and NRC (2001), respectively. However, INRA (1989), SCA (1990), and AFRC (1993, +0.05) predicted the milk production relatively well.

AFRC (1990) reported an evaluation of production data of lactating dairy cows from three research centers in the UK using ARC (1980), and an early and similar version of AFRC (1990 and 1993). Although total ME requirement was overpredicted and milk yield underpredicted with one center and with two centers, the total ME requirement was predicted to be 0.94 and 0.96 of actual ME intake and, accordingly, the milk yield was predicted to be 1.12 and 1.05 of actual milk yield.

The underprediction of total ME requirement by AFRC (1990 and 1993) could mainly be derived from the underestimated ME_m , because the k_l values predicted from ME/GE in the present study were unlikely to be overpredicted. The mean predicted k_l (0.64) of AFRC (1990 and 1993) in the present study is the same as that recommended by NRC (2001) and within the range (0.62–0.67) of k_l values with calorimetric data of dairy cows reported recently (Unsworth et al., 1994; Yan et al., 1997a; Cammell et al., 2000). The mean k_l value across those studies is also 0.64. The ME requirements for lactation and LWC predicted from AFRC (1990 and 1993) are, thus, unlikely to be underestimated in the present evaluation. The underestimated part is likely to be the ME_m . This can be demonstrated in the evaluation of SCA (1990) which uses the same k_l as AFRC (1990 and 1993) but a greater ME_m by adjusting it with total ME intake. In the present study, the mean ME_m values predicted from AFRC (1990 and 1993) were 0.478 and 0.482 MJ/kg^{0.75}, respectively, which is proportionately 0.23 lower than that predicted from SCA (1990; 0.590 MJ/kg^{0.75}) and also lower than those (0.59 – 0.67 MJ/kg^{0.75}) reported recently with calorimetric data (as mentioned previously). In recognition of this problem, an addition of proportionately 0.05 to the total ME requirement from AFRC (1993) is adopted in practice in the UK (1993, +0.05). This solution is, however, not justified scientifically.

Agnew and Yan (2000) reviewed published data from the last three decades and reported that the NE_m derived from data over 30 yr ago and currently used in Europe and North America is lower than that for the current dairy cows. This may be a consequence of changes in the diets offered and genotypes of cows now

used. For example, high genetic merit cows used in recent studies may have a greater proportion of live weight as body protein mass than medium- and low-genetic merit animals (Veerkamp et al., 1994; Ferris et al., 1999). On the other hand, high-genetic merit cows tend to have greater nutrient intakes, and this could stimulate the activity of internal organs with greater digestive load, cardiac output, and blood flow required to digest, absorb, and deliver nutrients to the mammary gland and a greater oxygen consumption (Reynolds, 1996).

In the three NE systems (Van Es, 1978; INRA, 1989; NRC, 2001), k_m is assumed to be equal to k_l to calculate NEL. As a consequence of this simplification, there is no basis to make a direct comparison of the evaluation between ME and NE systems. However, this assumption is not biologically correct, because research evidence has indicated k_m to be greater than k_l (ARC, 1980). The difference between k_m and k_l is calculated to be proportionately 0.12 or 0.08 in Van Es (1975) or ARC (1980) when ME/GE ratios are from 0.55 to 0.70. The assumption that k_m is equal to k_l could, thus, be responsible for the underprediction of NE_m used in the three NE systems, because the metabolic rates, as reported by Agnew and Yan (2000), are similar between the three NE systems and AFRC (1990 and 1993). The underprediction of NE_m would be 4.3 or 4.5 MJ/d for Van Es (1978) and INRA (1989) or NRC (2001) when using k_m and k_l of AFRC (1990) and the mean values of ME/GE and live weight in the present study. This bias would be larger for late-lactating and dry cows because the ratios of ME_m/ME_{int} (ME intake) is greater at these two stages. Nevertheless, there are some differences between the three NE systems which resulted in the different evaluations between them. For example, in NRC (2001) and INRA (1989), unlike in Van Es (1978), an activity allowance of proportionately 0.10 is added to NE_m . The k_l value in NRC (2001) is greater than that in Van Es (1978) and INRA (1989), e.g., in the present study the derived k_l values were, respectively, 0.634 and 0.616 [see equations (4) and (5)].

Prediction of Live Weight Change

The prediction of LWC was very poor with all systems tested in the present study, although the mean predicted LWC was the same as the mean actual LWC with SCA (1990) and INRA (1989). With each system, the standard error or MPE value was considerably large, and the error derived from the line (slope) accounted for 0.49 or more of total MSPE, indicating that there was a substantial variation between the predicted and actual LWC among the individual cows. Furthermore, the residual plots of the residual LWC (predicted

– actual) against predicted LWC revealed that the prediction error was greater with increasing predicted LWC for all systems evaluated in the present study. Heuer et al. (2001) also reported a positive relationship between the residual LWC and predicted LWC in the prediction of herd mean energy balance of dairy cows for the first 12 wk of lactation. These findings reflect the inaccuracy associated with the use of LWC as an indication of the energy balance for lactating dairy cows. There are many experimental and physiological factors that influence the energy content per unit of LWC. For example, the time of day that live weight is measured and the health of the cow at the time of measurement can influence the live weight recorded (amount of feed and water that the cow eats and drinks). These effects would, however, be minimized in the present study, as the LWC was obtained from the linear regression of at least eight continuous weekly live weights. In addition, the body condition of cows can influence the chemical composition of LWC, such as the amount of gain or loss of body fat or protein. The fat contains more energy than protein (39.3 v. 23.2 MJ/kg; NRC, 2001).

A further factor affecting energy value per unit of LWC is the stage of lactation. During early lactation, dairy cows can mobilize both fat and protein from their body reserves for milk production, but protein mobilization decreases faster than fat (Reid and Robb, 1971; Tamminga et al., 1997). For example, protein mobilization is stopped at about 4 wk after calving, while fat mobilization may continue for more than 8 wk (Tamminga et al., 1997). This may be due to hypertrophy of both gut and liver during early lactation in response to increased feed intake (Reynolds and Beever, 1995). The composition of mobilized tissue (fat and protein) can, thus, differ during the first 4 wk of lactation, i.e., the fat:protein ratio would increase. If the water content in mobilized tissue is assumed to remain unchanged, the energy value per unit of live weight loss would increase as lactation progresses. On the other hand, energy balance is not always related to LWC of dairy cows. Beever et al. (1998) reported that high genetic merit cows were still in negative energy balance at 20 wk of lactation, but live weight of the animals was maintained after 5 wk. Cammell et al. (2000) reported that lactating dairy cows consistently gained live weight from 6 to 24 wk of lactation, but the energy balance of the cows was nearly zero during the same period. This can be partially explained by the findings of Tamminga et al. (1997), as changes in the water content in mobilized live weight. The total water loss was proportional to the mobilized live weight during the first 4 wk of lactation. Afterwards, animals retained water in their bodies, and live weight loss was very

small, but energy loss was still high (Tamminga et al., 1997). Energy value per unit of mobilized live weight, thus, increased substantially from 1 to 8 wk of lactation (Tamminga et al., 1997). Therefore, at the early stage of lactation, LWC is an independent index of body tissue mobilization (Sutter and Beever, 2000). The LWC is not an appropriate indication of energy balance for lactating dairy cows as currently adopted worldwide.

CONCLUSIONS

The present evaluation indicated that INRA (1989) and SCA (1990) predicted the total energy requirement and milk production in dairy cows more accurately than Van Es (1978), AFRC (1990 and 1993), and NRC (2001). The latter three systems underpredicted total energy requirement of lactating dairy cows, which may restrict the production potential of cows when using these systems to formulate diets. The prediction error of AFRC (1990 and 1993) can be minimized by an addition of proportionately 0.05 to the total ME requirement predicted by AFRC (1993), as currently adopted in the UK. However, all of the systems evaluated in the present study had a poor prediction of LWC, with considerably large variations between predicted and actual LWC among individual cows. LWC alone is an inappropriate indication of energy balance for lactating dairy cows as currently adopted worldwide. This area merits further research to improve the current energy feeding systems for dairy cows.

ACKNOWLEDGMENTS

The authors thank their colleagues at the Agricultural Research Institute of Northern Ireland and the Moorepark Research Centre in Southern Ireland for access to the production and calorimetric data used in the present study.

REFERENCES

- Agnew, R. E., and T. Yan. 2000. The impact of recent research on energy feeding systems for dairy cattle. *Livest. Prod. Sci.* 66:197–215.
- Agnew, R. E., and T. Yan. 2002. The relationship between metabolizable energy concentration and nutrient digestibility in grass silage offered to sheep at maintenance. Page 51 In *Proc. Br. Soc. Anim. Sci.*, York, UK.
- Agricultural and Food Research Council (AFRC). 1990. Technical Committee on Responses to Nutrients, Report Number 5, Nutritive Requirements of Ruminant Animals: Energy. *Nutr. Abstr. Rev. (Series B)* 60:729–804.
- Agricultural and Food Research Council (AFRC). 1993. Energy and protein requirements of ruminants. CAB International, Wallingford, Oxon, UK.
- Agricultural Research Council (ARC). 1980. The Nutrient Requirements of Ruminant Livestock, Technical Review. Farnham Royal, CAB, UK.

- Beever, D. E., S. B. Cammell, J. D. Sutton, and D. J. Humphries. 1998. The effect of stage of harvest of maize silage on the concentration and efficiency of utilisation of metabolizable energy by lactating dairy cows. Pages 359–363 in *Energy Metabolism of Farm Animals*. K. McCracken, E. F. Unsworth and A. R. G. Wylie, ed., CAB Int., Wallingford, Oxon, UK.
- Cammell, S. B., D. E. Beever, J. D. Sutton, J. France, G. Alderman, and D. J. Humphries. 2000. An examination of energy utilization in lactating dairy cows receiving a total mixed ration based on maize silage. *Anim. Sci.* 71:585–596.
- Ferris, C. P., F. J. Gordon, D. C. Patterson, C. S. Mayne, and D. J. Kilpatrick. 1999a. The influence of dairy cow genetic merit on the direct and residual response to level of concentrate supplementation. *J. Agric. Sci. (Camb.)* 132:467–481.
- Ferris, C. P., F. J. Gordon, D. C. Patterson, M. G. Porter, and T. Yan. 1999b. The effect of genetic merit and concentrate proportion in the diet on nutrient utilization by lactating dairy cows. *J. Agric. Sci. (Camb.)* 132:483–490.
- Fitzgerald, S., J. Murphy, and F. O'Mara. 1994. Effect of replacing grass silage with low- or moderate-quality maize silage on milk production of dairy cows. Pages 93–94 in 20th Ann. Res. Mtg Irish Grassl. Anim. Prod. Assoc., Univ. Coll. Dublin, Ireland.
- Fitzgerald, S., and J. J. Murphy. 1999. A comparison of low-starch maize silage and grass silage and the effect of concentrate supplementation of the forages or inclusion of maize grain with the maize silage on milk production by dairy cows. *Livest. Prod. Sci.* 57:95–111.
- Heuer, C., W. M. van Straalen, Y. H. Schukken, A. Dirkzwager, and J. P. T. M. Noordhuizen. 2001. Prediction of energy balance in high-yielding dairy cows with test-day information. *J. Dairy Sci.* 84:471–481.
- Givens, D. I., J. M. Everington, and A. H. Adamson. 1989. The digestibility and metabolizable energy content of grass silage and their prediction from laboratory measurements. *Anim. Feed Sci. Technol.* 1989. 24:27–43.
- Institut National de la Recherche Agronomique (INRA). 1989. Ruminant nutrition—Recommended allowances and feed tables. John Libbey Eurotext, Paris-London-Rome.
- Keady, T. W. J., and J. J. Murphy. 1996. Effects of inoculant treatment on ryegrass silage fermentation, digestibility, rumen fermentation, intake, and performance of lactating dairy cattle. *Grass Forage Sci.* 51:232–241.
- Keady, T. W. J., and J. J. Murphy. 1997. The effect of treating low dry-matter herbage with a bacterial inoculant or formic acid on the intake and performance of lactating dairy cattle. *Anim. Sci.* 64:25–36.
- Keady, T. W. J., and C. S. Mayne. 1998. The effects of concentrate energy source on silage feeding behavior and energy utilization by lactating dairy cows offered grass silages with differing intake characteristics. *Anim. Sci.* 67:225–236.
- Keady, T. W. J., C. S. Mayne, D. A. Fitzpatrick, and M. Marsden. 1999. The effects of energy source and level of digestible undegradable protein in concentrates on silage intake and performance of lactating dairy cows offered a range of grass silages. *Anim. Sci.* 68:763–777.
- Keady, T. W. J., J. J. Murphy, and D. Harrington. 1999. The effects of ensiling on dry-matter intake and milk production by lactating dairy cattle given forage as the sole feed. *Grass Forage Sci.* 51:131–141.
- Mayne, C. S., and F. J. Gordon. 1984. The effect of type of concentrate and level of concentrate feeding on milk production. *Anim. Prod.* 39:65–76.
- National Research Council (NRC). 2001. Nutrient Requirements of Dairy Cattle. 7th rev. ed., Natl. Acad. Sci., Washington, DC.
- O'Mara, F., S. Fitzgerald, J. J. Murphy, and J. J. Rath. 1998. The effect on milk production of replacing grass silage with maize silage in the diet of dairy cows. *Livest. Prod. Sci.* 55:79–87.
- Patterson, D. C., T. Yan, and F. J. Gordon. 1996. The effects of wilting of grass prior to ensiling on the response to bacterial inoculation. 2. Intake and performance by dairy cattle over three harvests. *Anim. Sci.* 62:419–429.
- Reid, J. T., and J. Robb. 1971. Relationship of body composition to energy intake and energetic efficiency. *J. Dairy Sci.* 54:553–563.
- Reynolds, C. K. 1996. Nutritional requirements of the high genetic merit dairy cow: constraints of feeding grasses and legumes. In *Grass and Forage for Cattle of High Genetic Merit*. Br. Grassl. Soc., Great Malvern, England.
- Reynolds, C. K., and D. E. Beever. 1995. Energy requirements and responses: a UK perspective. Pages 31–41 in *Breeding and Feeding the High Genetic Merit Dairy Cow*. T. L. J. Lawrence, F. J. Gordon, and A. Carson, ed. Br. Soc. Anim. Sci. Occasional Publ., No 19.
- Rook, A. J., M. S. Dhanoa, and M. Gill. 1990. Prediction of the voluntary intake of grass silages by beef cattle. 3. Precision of alternative prediction models. *Anim. Prod.* 50:455–466.
- Schwager-Suter, R., C. Stricker, D. Erdin, and N. Künzi. 2001. Net energy efficiencies of Holstein, Jersey and Holstein-Jersey F1-crosses. *Anim. Sci.* 72:335–342.
- Standing Committee on Agriculture (SCA). 1990. Feeding standards for Australian livestock - Ruminants. CSIRO, Australia.
- Sutter, F., and D. E. Beever. 2000. Energy and nitrogen metabolism in Holstein-Friesian cows during early lactation. *Anim. Sci.* 70:503–514.
- Tamminga, S., P. A. Luteijn, and R. G. M. Meijer. 1997. Changes in composition and energy content of liveweight loss in dairy cows with time after parturition. *Livest. Prod. Sci.* 52:31–38.
- Tyrrell, H. F., and J. T. Reid. 1965. Prediction of the energy value of cow's milk. *J. Dairy Sci.* 48:1215–1223.
- Unsworth, E. F., C. S. Mayne, A. Cushnahan, and F. J. Gordon. 1994. The energy utilization of grass silage diets by lactating dairy cows. Pages 179–181 in *Energy Metabolism of Farm Animals*. J. F. Aguilera, ed. Europ. Assoc. Anim. Prod., Publ. No. 76, Mojacar, Spain.
- Van Es, A. J. H. 1975. Feed evaluation for dairy cows. *Livest. Prod. Sci.* 2:95–107.
- Van Es, A. J. H. 1978. Feed evaluation for ruminants. 1. The systems in use from May 1977 onwards in The Netherlands. *Livest. Prod. Sci.* 5:331–345.
- Veerkamp, R. F., G. Simm, and J. D. Oldham. 1994. Effects of interaction between genotype and feeding system on milk production, feed intake, efficiency, and body tissue mobilization in dairy cows. *Livest. Prod. Sci.* 39:229–241.
- Yan, T., D. C. Patterson, F. J. Gordon, and M. G. Porter. 1996. The effects of wilting of grass prior to ensiling on the response to bacterial inoculation. 1. Silage fermentation and nutrient utilization over three harvests. *Anim. Sci.* 62:405–417.
- Yan, T., F. J. Gordon, R. E. Agnew, M. G. Porter, and D. C. Patterson. 1997a. The metabolizable energy requirement for maintenance and the efficiency of utilization of metabolizable energy for lactation by dairy cows offered grass silage-based diets. *Livest. Prod. Sci.* 51:141–150.
- Yan, T., F. J. Gordon, C. P. Ferris, R. E. Agnew, M. G. Porter, and D. C. Patterson. 1997b. The fasting heat production and effect of lactation on energy utilization by dairy cows offered forage-based diets. *Livest. Prod. Sci.* 52:177–186.
- Yan, T., D. C. Patterson, and F. J. Gordon. 1998. The effect of two methods of feeding the concentrate supplement to dairy cows of high genetic merit. *Anim. Sci.* 67:395–403.
- Yan, T., R. E. Agnew, F. J. Gordon, and M. G. Porter. 2000. The prediction of methane energy output in dairy and beef cattle offered grass silage-based diets. *Livest. Prod. Sci.* 64:253–263.