Increasing milk solids production across lactation through genetic selection and intensive pasture-based feed system

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ABSTRACT

The objective of the study was to quantify the effect of genetic improvement using the Irish total merit index, the Economic Breeding Index (EBI), on overall performance and lactation profiles for milk, milk solids, body weight (BW), and body condition score (BCS) within 2 pasture-based systems of milk production likely to be used in the future, following abolition of the European Union's milk quota system. Three genotypes of Holstein-Friesian dairy cattle were established from within the Moorepark dairy research herd: LowNA, indicative of animals with North American origin and average or lower genetic merit at the time of the study; HighNA, North American Holstein-Friesians of high genetic merit; and HighNZ, New Zealand Holstein-Friesians of high genetic merit. Animals from within each genotype were randomly allocated to 1 of 2 possible pasture-based feeding systems (FS): 1) The Moorepark pasture (MP) system (2.64 cows/ha and 344 kg of concentrate supplement per cow per lactation) and 2) a high output per hectare (HC) system (2.85 cows/ha and 1,056 kg of concentrate supplement per cow per lactation). Pasture was allocated to achieve similar postgrazing residual sward heights for both treatments. A total of 126, 128, and 140 spring-calving dairy cows were used during the years 2006, 2007, and 2008, respectively. Each group had an individual farmlet of 17 paddocks and all groups were managed similarly throughout the study. The effects of genotype, FS, and the interaction between genotype and FS on milk production, BW, and BCS across lactation were studied using mixed models with factorial arrangements of genotype and FS accounting for the repeated cow records across years. No significant genotype by FS interaction was observed for any of the variables measured. Results show that milk solids production of the national average dairy cow can be increased across lactation through increased EBI. High EBI genotypes (HighNA and HighNZ) produced more

milk solids per cow and per hectare than the LowNA genotype (2.7 and 4.1%, respectively). The results also suggest that when concentrate supplementation is used to facilitate increased stocking rates, increased herbage utilization and decreased substitution of concentrate for herbage can be achieved. When implemented, the HC FS could increase the overall productivity of pasture-fed dairy farming systems where land availability is the primary limiting factor of production.

Key words: genotype, pasture-based feed system, milk solids production, lactation

INTRODUCTION

Irish milk production systems are characterized by a pasture-based diet with smaller production costs within a European Union (EU) context (Dillon et al., 2008). With the proposed abolition of EU milk quotas by 2015, Lips and Rieder (2005) project that milk production within the EU will move to areas of competitive advantage and anticipate a 38% increase in Irish milk output. The realization of this expansion will require increased productivity from pasture without increasing the requirement for higher cost external supplements. With land availability the likely long-term limitation to increased productivity, the objective of Irish production systems will be to increase productivity per unit of available feed through increased grass production and utilization (Shalloo et al., 2004). Such adaptations have occurred in other pasture-based countries and are characterized by increased stocking densities (Philpott, 1995) and adjustments to breeding objectives (Harris et al., 1996) to increase production efficiency.

Many dairy production experiments under grazing conditions have observed increased production per hectare as stocking rates increased while production per cow declined (Journet and Demarquilly, 1979; MacDonald et al., 2008). Penno (1999) suggested that the ideal stocking rate should balance the dual objectives of generous feeding to achieve high levels of efficiency of milk production per cow and underfeeding to achieve high levels of pasture utilization to meet the overall objective of optimizing farm profitability. On that

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Table 1. Number of cows and lactation records within each genotype and feed system for each year of the study

Item	Genotype ¹			Feed system ²	
	LowNA	HighNA	HighNZ	MP	HC
Animals (n)					
Yr 1	42	42	42	63	63
Yr 2	42	42	44	64	64
Yr 3	46	46	48	70	70
Lactation records (n)					
Parity 1	40	40	43	62	61
Parity 2	35	28	32	50	45
Parity 3+	59	63	58	87	93

¹Genotype: LowNA = national average-genetic-merit North American Holstein-Friesian, HighNA = high-genetic-merit North American Holstein-Friesian, HighNZ = high-genetic-merit New Zealand Holstein-Friesian.

²Feed systems: MP = Moorepark, HC = high output per hectare.

basis, intensified systems require grazing management practices that maximize pasture production and quality and, in combination with increased stocking density, will result in increased milk productivity. Postgrazing residual sward height influences the rate of net pasture production (total production less senescence) by the sward with maximum net pasture production achieved at residual grazing heights of between 35 and 55 mm (Bircham and Hodgson, 1983; Lee et al., 2008). Recent experiments within Irish pasture-based systems (McEvoy et al., 2009) have documented increased grass quality and utilization as well as increased milk production per hectare in response to increased grazing severity of pastures in spring and early summer.

Within intensive pasture-based feed systems (**FS**), pasture supply is limited and animals that can convert restricted volumes of pasture into greater volumes of milk solids (**MS**; kg of fat plus protein) without repercussions on functionality will maximize productivity. The Irish total merit index, the Economic Breeding Index (**EBI**), launched in Ireland in 2001, is a dairy cattle breeding objective derived under Irish conditions to identify genetically superior animals for profitability (Berry et al., 2007). Traits included in the EBI (relative emphasis in parentheses) are milk production (42%), fertility (37%), beef performance (9%), calving performance (8%), and health (5%) (Berry et al., 2007). The index selects for fat and protein yield with a negative weighting on volume and includes functional traits such as fertility, health, and longevity. Similarly in New Zealand, genetic selection was initially focused on fat yield, but subsequently included protein yield, live weight, and survival (Harris et al., 1996). The net effect of these breeding goals is an animal that produces less milk volume but with greater milk composition; New Zealand animals are also likely to be lighter than animals from other countries (McCarthy et al., 2007). Pryce et al. (2005) observed that animals with lesser BW are

capable of superior MS productivity within intensive pasture-based systems because of their reduced maintenance requirements and increased production per unit of feed eaten. Lactation curve analysis has previously been used to elucidate the differences between various genotypes and FS within pasture-based systems (Horan et al., 2005a; Roche et al., 2006; McCarthy et al., 2007). The objective of this study, therefore, was to quantify the effect of genetic improvement using EBI on MS production, BW, and BCS across lactation within 2 likely future pasture-based systems of milk production.

MATERIALS AND METHODS

A more detailed description of the strains of Holstein-Friesian (**HF**), FS, and experimental design was reported previously (Coleman et al., 2009). This study was carried out at Moorepark Dairy Research Centre in the Republic of Ireland (55°10'N, 8°16'W) over a 3-yr period (2006, 2007, and 2008). A total of 391 lactations from 219 spring-calving dairy cows were studied, with 126, 128, and 140 cows in yr 1, 2, and 3, respectively (Table 1).

Animals

Three genotypes of HF dairy cattle were established for this study from within the Moorepark dairy research herd, based on their origin and overall genetic merit as measured using EBI (Table 2). The genotypes of HF compared were 1) animals indicative of the current Irish national population of North American HF origin (**LowNA**); 2) animals with high genetic potential of North American HF origin (**HighNA**); and 3) animals with high genetic potential of New Zealand HF origin (**HighNZ**). The average percentage of North American Holstein genes in the LowNA and HighNA animals was 90% compared with 12.5% for HighNZ animals. The

Table 2. Mean Economic Breeding Index (EBI) and EBI subindices for 3 strains of Holstein-Friesian cows studied based on their PTA for milk production, calving interval, and survival (range in parentheses where appropriate)

Item	Genotype ¹			SD
	LowNA	HighNA	HighNZ	
Animals (n)	76	69	73	
EBI	48.8 ^a (−34.7 to 91.4)	74.6 ^b (37.6 to 146.7)	87.8 ^c (32.5 to 108.2)	26.66
Subindex ^{2,3}				
Milk (€)	41.9 ^a (17.8 to 71.0)	40.0 ^a (−6.1 to 73.9)	47.8 ^b (30.9 to 67.4)	11.68
Fertility (€)	5.3 ^a (−89.9 to 52.8)	25.7 ^b (−3.0 to 75.6)	41.7 ^c (10.5 to 54.5)	23.79
Calving (€)	8.5 ^a (−11.4 to 19.9)	13.6 ^b (0.68 to 27.9)	17.2 ^c (1.11 to 25.6)	3.65
Beef (€)	−4.5 ^a (−17.2 to 2.9)	−3.7 ^b (−14.8 to 2.8)	−14.2 ^c (−24.9 to −0.1)	3.02
Health (€)	−2.4 ^a (−9.3 to 5.5)	−1.0 ^a (−6.6 to 5.0)	−4.7 ^b (−10.8 to −0.2)	6.27

^{a-c}Means within a row with different superscripts differ ($P < 0.05$).

¹Genotype: LowNA = national average-genetic-merit North American Holstein-Friesian, HighNA = high-genetic-merit North American Holstein-Friesian, HighNZ = high-genetic-merit New Zealand Holstein-Friesian.

²Obtained from the March 2008 genetic evaluations.

³Milk = kilograms of fat + kilograms of protein − kilograms of milk; fertility = calving interval and survival; calving = direct calving difficulty, maternal calving difficulty, gestation length, and mortality; health = locomotion and SCC; beef = carcass BW, carcass conformation, carcass fat, and cull cow value.

LowNA group was selected to represent the characteristics of the average genetic potential dairy cow on Irish dairy farms at the time of the study (Irish Cattle Breeding Statistics; ICBF, 2008). These animals were used as a base to quantify the capacity for productivity of the average Irish dairy cow within future intensive production systems. The HighNA genotype was generated to represent the effect of genetic improvement using high-EBI North American HF sires. The HighNZ group was used to compare the effects of genetic improvement through high-EBI New Zealand HF ancestry compared with North American HF ancestry of equally high overall genetic merit. The HighNZ herd represents a HF that was selected within a seasonal pasture-based system similar to that in Ireland, but with a greater emphasis on milk composition, compact seasonal-calving fertility targets, and decreased BW. Both high-EBI genotypes reflect animals that were representative of the top 10% of dairy cows in Ireland for that particular genotype at the time of the study. Mean parity structure (2.2 lactations) was not different across genetic groups or FS. Regardless of fertility performance, equal numbers of replacements were introduced each year to maintain a parity structure across genotypes and FS.

Feed Systems and Grazing Management

All pluriparous animals were randomly allocated to 1 of 2 possible post-EU milk quota pasture-based FS: 1) the Moorepark pasture (**MP**) system; a high grass

allowance, high stocking rate (2.64 cows/ha), and low concentrate input (344 kg/cow) system, and 2) a high output per hectare (**HC**) system; a higher stocking rate (2.85 cows/ha) system with an increased concentrate input (1,056 kg/cow). The MP FS was designed as a low-cost pasture management system for a post-EU milk quota scenario based on high levels of pasture utilization and a low level of concentrate supplementation. The HC FS was created as a high-productivity pasture system to increase milk output per hectare by supplementing pasture with concentrates and increasing stocking rate to ensure similar high levels of pasture utilization. Both FS grazed to a similar postgrazing residual sward height during the experiment. Each FS was also defined in terms of comparative stocking rate (Macdonald et al., 2008) as an alternate measure of FS intensity. Comparative stocking rate was similar across all genotypes (100, 100, and 96 kg of BW/t of DM for the HighNA, LowNA, and HighNZ genotypes, respectively) and FS (101 and 96 kg of BW/t of DM for the MP and HC FS, respectively).

Cows were turned out to pasture immediately postpartum and grazed whenever weather conditions allowed, only returning indoors under severe weather conditions. Turnout occurred on January 23, January 24, and January 28 in yr 1, 2, and 3, respectively. The artificial fertilizer application rate was constant for all treatments at 250, 310, and 246 kg of N per hectare in yr 1, 2 and 3, respectively. Grazing management was accomplished by weekly monitoring of farm grass cover

Table 3. Grazing description and dietary details for the Moorepark pasture (MP) and high output per hectare (HC) feed systems during the experiment

Item	Feed system		SE ¹	Significance
	MP	HC		
Pregrazing sward height (cm)	10.4	10.5	0.09	0.66
Postgrazing sward height (cm)	4.8	4.7	0.50	0.42
Pregrazing herbage mass (kg of DM/ha)	1,553	1,545	105.0	0.80
Herbage allowance (kg of DM/cow/d)	16.0	14.7	0.98	<0.001
Concentrate fed				
kg of DM/cow	344	1,056	11.8	<0.001
kg of DM/ha	893	2,971	33.1	<0.001
kg of DM/cow/d	1.2	3.6	0.04	<0.001
Total daily allowance (kg/d)	17.2	18.3	0.08	<0.001

¹SE = pooled standard error.

with pasture quality maintained by removal of surplus grass as silage throughout the experiment (O'Donovan, 2000). All groups were managed similarly on a common rotation length and grazed similar pregrazing herbage masses (>4 cm, Table 3). Residency times were determined by the achievement of a target postgrazing residual sward height of 5 cm in yr 1 and 2 and 4 cm in yr 3. To account for the stocking rate differential, paddock sizes were 8% smaller for the HC FS than for the MP FS. Consequently, daily herbage allowance was 8% greater for the MP FS compared with the HC FS and a mean differential of 2.4 kg DM of concentrate per cow per day was maintained between the MP and HC FS throughout the grazing season. The ingredient composition of the concentrate feed (kg/t as fed) was as follows: barley 250, corn gluten 260, beet pulp 350, soybean meal 110, and minerals plus vitamins 30.

Grass and Concentrate Chemical Analysis

Samples collected for chemical analysis were bulked for each experimental week and analyzed for DM content, ash, ADF, and NDF (Ankom Technology, Macedon, NY), organic matter digestibility (Fibred Systems, Foss, Ball Mount, Dublin, Ireland), and CP (Leco FP-428, Leco Australia Pty Ltd., Castle Hill, New South Wales, Australia). Concentrate samples were collected weekly. These samples were then bulked for each month and were analyzed for DM, ash, CP, NDF, and crude fiber. Silage samples were collected twice weekly while the cows were indoors and bulked for each experimental week. Silage samples were analyzed for DM, ash, CP, NDF, and ADF.

Pasture Measurements

Pregrazing herbage mass (>4 cm horizon) was determined before grazing in each paddock for each genotype and FS based on 2 strips (0.70 m wide, 7 m long) of

grass cut with an Agria mower (Agria-Werke GmbH, Mockmuhl/Wurt, Germany). The herbage from each strip was weighed, and a subsample was taken and dried for 16 h at 95°C for DM determination. A further composite sample was collected for each genotype. This sample was dried for 48 h at 40°C, milled through a 1-mm sieve, and analyzed for chemical analysis. Ten grass height measurements were recorded before and after harvesting on each cut strip using an electronic plate meter with a plastic plate (30 × 30 cm and 4.5 kg/m², Agrosystèmes, Choiseille, France). Based on the above measurements it was possible to measure sward density, as follows:

$$\text{Sward density} = [\text{herbage mass (kg of DM/ha)} / (\text{precutting height} - \text{postcutting height}); \text{kg of DM/cm per ha}].$$

An additional 30 sward heights were taken before grazing and 30 heights were taken after grazing. These sward heights in combination with sward density were used to calculate average paddock pregrazing herbage mass:

$$\begin{aligned} \text{Pregrazing herbage mass} = & \{[\text{pregrazing sward height} \\ & (\text{mm}) - \text{postgrazing residual sward height (mm)}] \\ & \times \text{sward density; kg of DM per ha}\}. \end{aligned}$$

Daily herbage allowance and group-average grass DMI could then be calculated based on pregrazing herbage mass and residency period within that paddock area. Postgrazing sward measurements were also used as an ongoing verification tool to ensure that target postgrazing residual heights were being maintained for each genotype and FS such that grazing severity and grass utilization was equal for all groups. Total annual pas-

ture production for each farmlet was calculated as the cumulative removal from all events of grazing and silage removal during the year, plus closing pasture herbage mass at year-end, minus opening pasture herbage mass at the start of the year for each paddock.

Animal Measurements

Cows were milked twice daily throughout lactation in all 3 years of the study. Milking took place at 0700 and 1530 h daily. Weekly milk production was derived from individual cow milk yield (kg) recorded at each milking (Dairymaster, Causeway, Co. Kerry, Ireland). Milk fat, protein, and lactose concentrations were determined in successive p.m. and a.m. samples of milk each week by using a Milkoscan 203 (DK-3400, Foss Electric, Hillerød, Denmark), and weekly MS and solids-corrected milk yield (SCM; Tyrell and Reid, 1965) were also calculated. Lactation milk and MS production per hectare was calculated by multiplying lactation yields by the annual stocking rate for each genotype and FS each year. Individual animal BW was recorded weekly upon exit from the milking parlor by using an electronic scale (Tru-Test Ltd., Auckland, New Zealand) calibrated weekly against known weights. Animal BCS was measured every 3 wk throughout the study on a 0 to 5 scale (0 = thin, 5 = fat) in increments of 0.25 as outlined by Edmonson et al. (1989). Body condition score was assigned by the same individual throughout the study.

Lactation Profiles

Lactation profiles for milk yield, MS yield, and BW were described by the Wilmink exponential function (Wilmink, 1987) using Proc NLIN (SAS Institute, 2006), fitted to weekly records within each lactation. The Wilmink exponential function is described as

$$Y_{\text{DIM}} = a + [b \times e^{(-0.05 \times \text{DIM})}] + c \times \text{DIM},$$

where Y_{DIM} = the dependent variable of interest on a particular DIM, a = the height of the curve, b = the first phase of the curve, and c = the second phase of the curve. A negative initial phase indicates an increase in the curve and a negative second phase indicates a decrease in the curve. Day of peak yield was estimated from the first derivative of the lactation profile and peak yield was taken at that DIM; similar methodology was used to estimate nadir BW and DIM of nadir BW. Residuals for each DIM were calculated as the difference between the actual value and the value predicted from the curve. The root mean square error of prediction was calculated for each cow-lactation as the standard

deviation of the residuals within each cow-lactation. Additionally, the r^2 value for each cow-lactation was calculated as 1 minus the residual sums of the squares divided by the corrected total sums of squares. Preliminary analysis showed a poor fit of the Wilmink function to the BCS data; therefore, a smoothing spline with 6 knot points at d 20, 70, 120, 170, 220, and 270 was fitted to the BCS data for each cow-lactation separately in ASREML (Gilmour et al., 2001). Daily solutions for BCS were obtained from the fitted curves.

Statistical Analysis

Dietary Details. Seasonal effects on the chemical composition of pasture, silage, and concentrate were determined using mixed models (Proc Mixed, SAS Institute, 2006) with experimental week included as a repeated effect; a compound symmetry covariance structure among records provided the best fit to the data. Year and season were included as fixed effects in the model. The effect of genotype, FS, and year on pregrazing yield, daily herbage allowance, pre- and postgrazing sward height, and annual concentrate supplementation was determined using mixed models (Proc Mixed, SAS Institute, 2006) with paddock included as a repeated effect; again, a compound symmetry covariance structure among records within paddock was most appropriate for the data.

Milk Production and BW Performance. The effects of genotype and FS on total lactation yields for milk, MS, and SCM, and milk composition per cow, as well as parameters derived from the 305-d lactation curves for BW and BCS, were determined using mixed models (Proc Mixed, Statistical Institute, 2006) with cow included as a repeated effect to account for the repeated lactations per cow; a compound symmetry covariance structure with heterogeneous variances provided the best fit to the data. In a separate series of analyses, the effects of genotype, FS, and year on lactation yields for milk, MS, and SCM production performance expressed per hectare were determined using mixed models (Proc Mixed, SAS Institute, 2006) with cow included as a repeated effect to account for multiple lactation records from the same animal; an unstructured covariance structure provided the best fit for the data. The dependent variable in these analyses was cow lactation yield multiplied by stocking rate (i.e., cows per hectare). Initial models included the effects for genotype, FS, parity, year, calving date, and interactions. Nonsignificant effects ($P > 0.05$) were removed from the models by backward elimination. Differences between high-EBI animals (i.e., HighNA and HighNZ) and LowNA as well as between HighNA and HighNZ were determined using orthogonal contrasts.

Table 4. Seasonal variation in the chemical composition (g/kg) of grass, concentrate, and grass silage

Item	Season				SE ¹	Significance
	Spring	Summer	Autumn	Winter		
Grass						
OM digestibility	789 ^{ab}	795 ^a	771 ^{ab}	742 ^b	11.7	0.04
CP	245 ^a	219 ^b	212 ^b	210 ^b	5.86	<0.001
NDF	446 ^{ab}	444 ^a	468 ^b	469 ^{ab}	8.67	0.02
ADF	263 ^a	257 ^a	288 ^b	292 ^b	5.88	<0.001
Ash	104 ^{ab}	85 ^c	96 ^{ac}	116 ^b	3.5	<0.001
Concentrates						
CP	167	155	156	155	4.2	0.29
NDF	278	273	294	290	14.0	0.58
Crude fiber	88 ^a	103 ^{ab}	113 ^b	100 ^{ab}	4.26	0.009
Ash	94	99	100	95	2.8	0.43
Silage						
CP	156			161	3.9	0.28
NDF	539			536	8.2	0.82
ADF	367			365	8.1	0.83
Ash	93			96	3.9	0.57

^{a-c}Means within a row with different superscripts differ ($P < 0.05$).

¹SE = pooled standard error.

RESULTS

Dietary Effects During Lactation

All animals were managed similarly across lactation and grazed similar pregrazing herbage masses with similar pregrazing heights (Table 3). Herbage allowance was lower for animals in the HC FS compared with animals on the MP FS (14.7 and 16.0 kg of DM per day for HC and MP FS, respectively) but received a greater total daily allowance when concentrate was included in the diet (18.3 and 17.2 kg of DM per day for HC and MP FS, respectively). Grass utilization, characterized by postgrazing sward height, was similar for both production systems. Paddock residency times were longest ($P < 0.001$) during the spring and autumn (3.4 and 3.0 d per paddock) when growth rates were low compared with summer months (1.9 d per paddock) because increased growth rates and stocking rates necessitated shorter rotations to maximize sward quality and utilization. Average rotation length in the spring and autumn was 50 d and 42 d, respectively, compared with 23 d in summer months. Total herbage production was similar for each FS and averaged 13.8 t of DM per hectare over the 3 experimental grazing seasons (10.6, 14.8, and 16.0 t of DM per hectare in 2006, 2007, and 2008, respectively). Dry matter production during yr 1 of the experiment was reduced because of a midsummer drought, whereas growth rates during 2007 and 2008 exceeded historical records at this research site (Dillon et al., 2005).

Differences in quality of grass, grass silage fed, and concentrates fed are displayed in Table 4. Grazed herbage quality was superior during the spring and summer

months with increased ($P < 0.05$) OM digestibility and lower NDF and ADF compared with that in the autumn and winter months. Grass CP content was greater in spring compared with the rest of the year. No seasonal differences were observed in concentrate quality with the exception of crude fiber, which was higher during autumn. Grass silage was only included in the milking cow diet from November to February, and no differences in quality were observed during these periods.

Lactation Milk Production

The effects of genotype and FS on milk production performance are displayed in Table 5. No interaction ($P > 0.05$) between genotype and FS was observed for any milk production traits. The HighNZ genotype produced the smallest volume of milk per cow (5,860 kg) and per hectare (16,311 kg), with the HighNA genotype producing the greatest (6,235 and 17,209 kg, respectively) and the LowNA genotype intermediate (6,333 and 16,950 kg, respectively). The HighNA animals produced the greatest amount of MS and SCM per cow (477 and 5,992 kg, respectively), whereas the LowNA produced the least (459 and 5,781 kg, respectively) and the HighNZ were intermediate (469 and 5,865 kg, respectively). The LowNA produced less MS and SCM per hectare (1,246 and 15,715 kg, respectively) compared with both the HighNA (1,294 and 16,285 kg, respectively) and HighNZ genotypes (1,313 and 16,354 kg, respectively). Milk fat, protein, and lactose concentrations were greatest for HighNZ animals (44.0, 35.7, and 46.0 g/kg, respectively), whereas there was no difference between the HighNA (40.9, 34.7, and 45.5 g/kg, respectively) and LowNA (39.7, 34.4, and 45.5 g/kg,

respectively) genotypes. Overall, high-EBI genotypes (HighNA and HighNZ) produced 2.7% more MS per cow and 4.1% more MS per hectare compared with the LowNA genotype.

Animals in the HC FS produced greater volumes of milk, MS, and SCM both per cow (6,440, 489, and 6,152 kg, respectively) and per hectare (18,244, 1,388, and 17,449 kg, respectively) than contemporaries in the MP FS (5,846, 447, and 5,507 kg per cow, and 15,402, 1,181, and 14,787 kg per hectare, respectively). Milk fat and protein concentrations were unaffected by FS, whereas lactose concentration was lower for the MP FS.

Lactation Profiles

The median R-square for the fit of the Wilmink function to milk yield, MS yield, and BW was 0.91, 0.84, and 0.70, respectively. There was no interaction between genotype and FS for any of the parameters of the lactation profile. The effect of genotype and FS on lactation parameters is displayed in Tables 5, 6, and 7 and Figures 1, 2, 3, and 4. On average, HighNZ animals had a lower lactation profile (i.e., the *a* parameter of the Wilmink function) for milk yield compared with HighNA and LowNA animals. The HighNA animals had a higher MS lactation profile than LowNA and HighNZ animals. The HighNA and LowNA animals exhibited similar lactation profiles whereas the HighNZ animals exhibited increased persistency (i.e., *c* parameter of the Wilmink function) for milk yield and MS yield compared with HighNA and LowNA animals. Peak milk yield and peak MS yield occurred at similar DIM for all genotypes, whereas peak milk and MS yield differences among genotypes followed a similar trend to differences in the height of the lactation curve (i.e., *a* parameter). The HighNA animals were heaviest, HighNZ the lightest, and the LowNA animals intermediate. The first (*b*) and second (*c*) phases of the BW lactation profile were not different between genotypes, with HighNZ animals being the lightest at all stages of lactation. At calving, HighNZ and HighNA animals had the greatest BCS (3.19 and 3.17 units, respectively) compared with LowNA animals (3.07 units). At the end of lactation, HighNZ animals had the greatest BCS (3.00 units) compared with both HighNA and LowNA animals (2.87 and 2.82 units, respectively) resulting in HighNZ animals having the greatest mean BCS across lactation (2.96 units) with LowNA animals having the least BCS across lactation (2.79 units) and HighNA animals intermediate (2.86 units). A genotype by parity interaction was observed for average lactation BCS in the data set whereby all genotypes lost body condition from first to second lactation, both the HighNA and LowNA continued to lose body condition over subsequent lactations,

Table 5. The effect of genotype (G)¹ and feeding system (F)² on lactation milk production and composition

Item	LowNA			HighNA			HighNZ			Significance ³				
	MP	HC		MP	HC		MP	HC	SE ⁴	G	F	G × F	High EBI vs. low EBI	HighNA vs. HighNZ
Milk yield														
kg/cow	5,954	6,562		6,034	6,636		5,558	6,201	100.4	<0.001	<0.001	0.96	0.18	<0.001
kg/ha	15,586	18,437		15,838	18,583		14,836	17,915	287.4	0.007	<0.001	0.75	0.82	0.009
Milk solids yield														
kg/cow	440	481		456	499		445	495	6.5	0.03	<0.001	0.64	0.017	0.13
kg/ha	1,151	1,354		1,197	1,396		1,189	1,433	18.3	0.002	<0.001	0.26	<0.001	0.45
SCM yield														
kg/cow	5,539	6,046		5,715	6,276		5,567	6,183	83.3	0.04	<0.001	0.73	0.04	0.07
kg/ha	14,486	17,001		14,999	17,582		14,887	17,884	235.7	0.009	<0.001	0.41	0.001	0.07
Milk composition														
Fat (g/kg of milk yield)	39.6	39.6		41.2	40.6		44.3	43.8	0.53	<0.001	0.18	0.72	<0.001	<0.001
Protein (g/kg of milk yield)	34.5	34.2		34.8	34.6		35.6	35.8	0.26	<0.001	0.60	0.19	<0.001	<0.001
Lactose (g/kg of milk yield)	45.4	45.6		45.3	45.7		45.9	46.1	0.15	<0.001	0.005	0.44	0.03	0.001

¹Genotype: LowNA = national average-genetic-merit North American Holstein-Friesian, HighNA = high-genetic-merit North American Holstein-Friesian, HighNZ = high-genetic-merit New Zealand Holstein-Friesian.

²Feed systems: MP = Moorepark pasture; HC = high output per hectare.

³G × F = genotype by feed system interaction; EBI = Irish Economic Breeding Index; High EBI = HighNA and HighNZ combined.

⁴SE = pooled standard error.

whereas the HighNZ genotype maintained BCS in later parities.

Animals on the HC FS achieved a greater incline in milk and MS yield postcalving but a similar decline post-peak to the animals on the MP FS. Peak yields occurred later in lactation for animals on the HC FS than for animals on the MP FS, with HC FS having greater peak milk yields but similar peak MS yields compared with MP FS. There was no effect of FS on BW at any stage of lactation. Animals on the HC FS had a similar BCS to animals on the MP FS at calving; however, BCS across lactation and at the end of lactation was greater for the animals on the HC FS compared with animals on the MP FS. There was no interaction between genotype of HF and FS for either BW or BCS measures.

DISCUSSION

Following the imminent abolition of EU milk quotas and the projected reduction in milk price, producers must focus on the efficiency of MS output per unit of land and feed (Dillon et al., 2008). On that basis, the identification of a production system that maximizes production per hectare from homegrown feed is imperative to sustain the profitability of pastoral farming into the future. Furthermore, the identification of a dairy cow that is capable of increased productivity within such a system will be equally important. The present study identified significant differences between genotypes of HF in production and productive efficiency when managed across 2 intensive pasture-based FS.

Effect of Genetic Improvement

Many studies have compared HF animals of high and low genetic potential for milk production traits within pasture-based systems and reported that high genetic line animals were associated with increased milk production and responses to additional feed (Kennedy et al., 2002; Fulkerson et al., 2008), reduced BCS (McCarthy et al., 2007), reduced persistency of lactation (Horan et al., 2005a), and inferior reproductive performance (Dillon et al., 2006). Kennedy et al. (2002) and Fulkerson et al. (2008) reported lower total lactation milk yields in HF cows with medium genetic merit compared with cows with high genetic merit for milk yield. Similarly, greater levels of milk production were observed among animals on high concentrate diets compared with those on low concentrate diets. These studies have invariably considered genetic merit exclusively within the context of milk production traits rather than total productive capacity and have been associated with decreased BCS, fertility, and survival (Dillon et al., 2006). The use of an

overall breeding goal allows the genetic characteristics of Irish dairy cattle to be described in terms of productive, reproductive, calving, and health traits.

The similar milk production per cow, increased milk composition, and consequently increased MS production throughout lactation and the superior BCS of HighNA animals compared with contemporaries of inferior genetic merit suggests that high-productivity North American Holstein genes suitable to pasture-based systems can be identified. Similarly, HighNZ animals having lower peak milk yield, greater persistency of production, and increased milk composition resulted in increased MS production compared with LowNA animals. Increased MS production coupled with superior BCS across lactations of both HighNA and HighNZ animals suggest that genetic improvement using a total merit index such as the EBI can increase MS production without negative effects on health and fertility. The superior milk composition of both HighNA and HighNZ genotypes within this study is also consistent with the increased milk subindex of these animals (Table 2). The lower overall milk production and greater composition of HighNZ compared with HighNA has been observed previously (Roche et al., 2006) and is consistent with the respective breeding objectives.

The differences in lactation profiles observed between genotypes suggest that animals with reduced peak MS production in combination with increased lactation persistency may be particularly useful within intensive pasture-based systems, assuming no difference in total lactation yield. The reduced energy demands for milk production in the HighNZ genotype in early lactation potentially present more energy for other body functions such as fertility performance. Consistent with this hypothesis, Coleman et al. (2009) reported superior pregnancy rates to first insemination among HighNZ animals compared with both HighNA and LowNA animals. The loss in BCS for all genotypes from first to second lactation is similar to the findings of Coffey et al. (2002). However, consistent with the findings of McCarthy et al. (2007), both the HighNA and LowNA animals continued to lose BCS over subsequent lactations, whereas the HighNZ genotype maintained BCS in later parities, which may account for the greater survival rates to greater lactations found by Coleman et al. (2009).

The effect of different feeding levels on animal performance has been reported to depend on the milk production potential of the animal (Leaver, 1985). Roche et al. (2006) found that animals of New Zealand origin had a lower milk production response to concentrate supplementation compared with North American HF animals, resulting in an increase of 0.67 and 1.22 kg of milk per additional kg of concentrate DM, re-

Table 6. The effect of genotype (G)¹ of Holstein-Friesian and feeding system (F)² on milk production lactation curve parameters

Item	LowNA		HighNA		HighNZ		SE ⁴	Significance ³				
	MP	HC	MP	HC	MP	HC		G	F	G × F	High EBI vs. low EBI	HighNA vs. HighNZ
Milk yield												
Wilmlink function parameters ⁵												
<i>a</i>	37.5	39.0	37.3	39.7	34.0	36.3	0.70	<0.001	<0.001	0.72	0.53	<0.001
<i>b</i>	−17.2	−18.0	−14.2	−20.9	−14.0	−18.5	1.14	0.01	<0.001	0.50	0.56	0.02
<i>c</i>	−0.11	−0.10	−0.10	−0.10	−0.09	−0.09	0.003	<0.001	0.65	0.30	0.77	<0.001
Peak milk yield (kg/cow/d)	30.8	32.0	30.7	32.5	28.0	29.7	0.56	<0.001	<0.001	0.84	0.42	<0.001
Day of peak milk yield	45.4	48.1	42.5	49.8	43.4	49.8	1.27	0.92	<0.001	0.17	0.66	0.96
Milk solids												
Wilmlink function parameters ⁵												
<i>a</i>	2.51	2.55	2.53	2.68	2.40	2.57	0.042	0.012	<0.001	0.19	0.04	<0.001
<i>b</i>	−0.55	−0.69	−0.34	−0.84	−0.39	−0.73	−0.810	0.74	<0.001	0.11	0.75	0.51
<i>c</i> (×10 ^{−2})	−0.62	−0.56	−0.60	−0.59	−0.52	−0.54	0.021	<0.001	0.32	0.19	0.36	<0.001
Peak milk solids yield (kg/cow/d)	2.24	2.27	2.33	2.32	2.19	2.28	0.043	0.03	0.26	0.47	0.02	0.02
Day of peak milk solids yield	32.1	38.3	23.4	40.0	27.7	40.3	2.68	0.37	<0.001	0.11	0.11	0.45

¹Genotype: LowNA = national average-genetic-merit North American Holstein-Friesian, HighNA = high-genetic-merit North American Holstein-Friesian, HighNZ = high-genetic-merit New Zealand Holstein-Friesian.

²Feed systems: MP = Moorepark pasture; HC = high output per hectare.

³G × F = genotype by feed system interaction; EBI = Irish Economic Breeding Index; High EBI = HighNA and HighNZ combined.

⁴SE = pooled standard error.

⁵Parameters *a*, *b*, and *c* are estimated parameters of an exponential function (milk yield_{*t*} = *a* + *b*e^{−0.5*t*} + *ct*), relating to the height of the lactation profile, the initial phase of post-calving incline to peak, and the subsequent post-peak decline phase, respectively.

Table 7. The effect of genotype (G)¹ of Holstein-Friesian and feeding system (F)² on BW and BCS lactation curve parameters

Item	LowNA		HighNA		HighNZ		SE ⁴	Significance ³				
	MP	HC	MP	HC	MP	HC		G	F	G × F	High EBI vs. low EBI	HighNA vs. HighNZ
BW												
Wilmink function parameters ⁵												
<i>a</i>	527.5	515.7	530.7	538.8	504.5	505.7	6.59	<0.001	0.65	0.24	0.01	<0.001
<i>b</i>	117.3	115.7	125.9	112.5	111.7	117.0	5.30	0.68	0.08	0.15	0.66	0.38
<i>c</i>	0.30	0.34	0.31	0.32	0.31	0.33	0.022	0.60	0.45	0.82	0.67	0.95
BW (kg)												
at calving	639	627	649	646	610	616	8.3	<0.001	0.60	0.48	0.03	<0.001
at dry off	617	620	612	628	579	588	24.1	<0.001	0.12	0.66	0.09	0.001
average BW	579	576	572	586	539	544	7.1	<0.001	0.29	0.39	0.006	<0.001
nadir BW	550	546	546	560	510	517	8.1	<0.001	0.65	0.30	0.003	<0.001
DIM at nadir BW (d)	68.1	58.5	61.2	58.7	63.1	59.4	4.2	0.72	0.07	0.59	0.47	0.92
BCS (units)												
at calving	3.05	3.09	3.16	3.17	3.18	3.20	0.030	<0.001	0.31	0.42	0.003	0.55
at dry off	2.79	2.85	2.81	2.93	2.98	3.02	0.033	<0.001	<0.001	0.34	0.03	0.001
average BCS	2.78	2.79	2.80	2.91	2.94	2.98	0.028	<0.001	0.02	0.19	0.009	0.002

¹Genotype: LowNA = national average-genetic-merit North American Holstein-Friesian, HighNA = high-genetic-merit North American Holstein-Friesian, HighNZ = high-genetic-merit New Zealand Holstein-Friesian.

²Feed systems: MP = Moorepark pasture; HC = high output per hectare.

³G × F = genotype by feed system interaction; EBI = Irish Economic Breeding Index; High EBI = HighNA and HighNZ combined.

⁴SE = pooled standard error.

⁵Parameters *a*, *b*, and *c* are estimated parameters of an exponential function ($BW_t = a + be^{-0.5t} + ct$), relating to the height of the lactation profile, the initial phase of postcalving incline to peak, and the subsequent post-peak decline phase, respectively.

spectively. In contrast, the observed milk production response to concentrate supplementation within the current experiment was similar in HighNA, LowNA, and HighNZ groups at 1.10, 1.14, and 1.22 kg of milk/kg of concentrate supplement, respectively, whereas the MS response was 0.080, 0.081, and 0.097 kg of MS/kg of concentrate supplementation, respectively. These results suggest that where nutrient supply is limited through increased grazing severity, large responses to additional supplementation can be achieved irrespective of the genetic potential for production of the animal, and this can increase MS production when concentrate to milk price ratios permit higher levels of concentrate supplementation.

Effect of System of Milk Production

Expansion in MS production within a limited land base will require the implementation of more intensive management systems. The ability to identify cows that can excel in terms of productive and reproductive performance within such systems will be of equal importance. Within the current experiment, systems designed for high overall stocking density and increased grass utilization provide a unique opportunity to evaluate the productive performance of various genotypes. The intensity of both FS within the current experiment is exemplified by the high comparative stocking rate (Macdonald et al., 2008) of both FS. Macdonald et al.

Figure 1. The effect of (top) genotype of Holstein-Friesian: HighNA (◆), LowNA (■), and HighNZ (▲), and (bottom) feed systems: MP (○) and HC (□), on the milk yield lactation curve. Genotypes: LowNA = national average-genetic-merit North American Holstein-Friesian, HighNA = high-genetic-merit North American Holstein-Friesian, HighNZ = high-genetic-merit New Zealand Holstein-Friesian; feed systems: MP = Moorepark pasture; HC = high output per hectare.

(2008) reported reduced milk production per cow but increased production per hectare under more intensive production systems through an increased comparative stocking rate. In contrast, increased stocking rate combined with increased concentrate supplementation (HC FS) within the current study created a comparative stocking rate and level of grass utilization similar to that of MP FS and resulted in increased overall levels of milk production per cow and per hectare. Further increases in production per hectare may be possible at even greater stocking rates although significant increases in concentrate supplementation would be required. The environmental effect of increased concentrate supplementation must be evaluated because increased

nitrogen and phosphorus inputs may have harmful effects, as previously observed by Ryan et al. (2010).

Although concentrate supplements are generally offered to pasture-fed dairy cows to alleviate shortfalls in herbage DM intake, increased stocking rates following abolition of the EU milk quota are likely to result in more frequent and prolonged periods of pasture deficit and a consequential requirement for more efficient pasture management and concentrate supplementation strategies. The current study demonstrated that increased concentrate supplementation in combination with an increased stocking rate resulted in increased milk productivity per cow and per hectare, greater and later peak milk production, and higher average BCS

Figure 2. The effect of (top) genotype of Holstein-Friesian: HighNA (♦), LowNA (■), and HighNZ (▲), and (bottom) feed systems: MP (○) and HC (□), on the milk solids lactation curve. Genotypes: LowNA = national average-genetic-merit North American Holstein-Friesian, HighNA = high-genetic-merit North American Holstein-Friesian, HighNZ = high-genetic-merit New Zealand Holstein-Friesian; feed systems: MP = Moorepark pasture; HC = high output per hectare.

throughout lactation. Previous studies have also observed a strong positive effect of higher levels of concentrate supplementation during lactation on milk production characteristics, BW, and BCS profiles compared with pasture-only diets (Horan et al., 2005a; McCarthy et al., 2007). Similarly, Journet and Demarquilly (1979) observed that as stocking rates increased by 1 cow per hectare, milk production per cow decreased by 10% and production per hectare increased by 20%. In the present study, as stocking rates increased by 0.21 cows per hectare above the predominantly pasture-based MP FS coupled with an increase of 2,078 kg of concentrate per hectare, production of milk and MS per hectare increased by 18.5 and 17.5%, respectively. This current

study further substantiates the hypothesis of Kellaway and Porta (1993), who suggested that concentrate supplementation could facilitate increased stocking rates to increase the efficiency of milk production per unit of land. Such approaches may become particularly relevant after abolition of milk quotas, when land availability restricts production from pasture.

Where grass supply is sufficient to meet demands, it is generally considered uneconomical to use supplements because of high grass substitution rates and low milk production responses to supplementary feeding (Holmes et al., 2002). In contrast, Shalloo et al. (2004) postulated that in a high-milk-price scenario, increased use of low-cost concentrate supplementation could en-

Figure 3. The effect of (top) genotype of Holstein-Friesian: HighNA ($\blacklozenge$), LowNA ($\blacksquare$), and HighNZ ($\blacktriangle$), and (bottom) feeding systems: MP ($\circ$) and HC ($\square$), on the BW lactation curve. Genotypes: LowNA = national average-genetic-merit North American Holstein-Friesian, HighNA = high-genetic-merit North American Holstein-Friesian, HighNZ = high-genetic-merit New Zealand Holstein-Friesian; feed systems: MP = Moorepark pasture; HC = high output per hectare.

hance the profitability of Irish pasture-based systems, where a response to concentrate in excess of 1.1 kg of milk per kg of additional concentrate can be achieved. The reduction in herbage DM intake observed in response to concentrate feeding under grazing conditions is dependent on herbage availability. Many previous studies have attempted to increase milk productive efficiency through increased concentrate supplementation; however, substitution rates resulting in reduced pasture utilization curtailed the benefits of these feeding strategies (Bargo et al., 2002). When herbage allowance is restricted, greater responses to concentrate feeding have been achieved (Leaver, 1985) because of a low substitution rate of concentrate for herbage (Meijs and Hoekstra, 1984). In this study, milk production per

hectare increased by 1.13 kg of milk and 0.083 kg of MS per kg of additional concentrate supplemented to HC FS. This high response to supplementary feed in HC FS is a consequence of an increased total DM allowance of 1.1 kg per cow among animals in the HC FS because of increased concentrate supplementation complemented with an increased stocking rate to maintain a moderate grass allowance and a high level of grass utilization, therefore minimizing the substitution rate of concentrate for herbage.

Enhancing Pasture Production

Average pasture production of 13.8 t of DM/ha was realized over the 3 yr of the current study, represent-

Figure 4. The effects of (top) genotype of Holstein-Friesian: HighNA (◆), LowNA (■), and HighNZ (▲), and (bottom) feeding systems: MP (○) and HC (□), on BCS across lactation. Genotypes: LowNA = national average-genetic-merit North American Holstein-Friesian, HighNA = high-genetic-merit North American Holstein-Friesian, HighNZ = high-genetic-merit New Zealand Holstein-Friesian; feed systems: MP = Moorepark pasture; HC = high output per hectare.

ing an 8% increase in total growth beyond previously recorded levels at this experimental site (Dillon et al., 2005; McCarthy et al., 2007) under comparable average climatic conditions, levels of artificial fertilization, and rate of pasture renewal. Grazing management within the current experiment was characterized by lower pregrazing herbage masses and increased grazing severity compared with previous experiments (Horan et al., 2005b). Consistent with the findings of Bircham and Hodgson (1983) and Lee et al. (2008), the increased net pasture productivity observed indicates the benefits of increased grazing severity to facilitate increased stocking rates through greater levels of pasture utilization.

Feed quality during the current experiment was similar to previously reported levels (Horan et al., 2005b), whereas the seasonal variability in sward quality from spring to autumn has been reported previously by Reed (1978). The post-spring decline in the nutritive value of available herbage has been observed by Baker (1980) with further reductions evident into autumn as the accumulation of dead material in the sward increases (Le Du et al., 1981). The higher digestibility and reduced structural carbohydrate (NDF) concentrations of spring and summer pastures is consistent with the findings of Binnie et al. (1997) and is explained by the reduced concentration of green leaf relative to mature stem and senescent material (Ulyatt, 1981). The higher CP concentration of spring pasture has also been observed previously and is associated with a reduction in the leafiness of the plant during the season and a reduction in the proportion of nutritionally desirable chloroplast proteins (Wheeler and Corbett, 1989).

CONCLUSIONS

Genotype of HF and pasture-based FS had a significant effect on the lactation characteristics of spring-calving dairy cows. The data show that aggressive selection using the Irish EBI will result in increased MS production and increased BCS across lactation. The results also suggest that when herbage allowance is restricted, increased concentrate supplementation will result in low substitution rates and increased efficiency of pasture-based FS.

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REFERENCES

- Baker, A. M. C. 1980. A study of herbage production and its utilisation by dairy cattle from continuously grazed swards. MS thesis. University of Glasgow, UK.
- Bargo, F., L. D. Muller, J. E. Delahoy, and T. W. Cassidy. 2002. Milk response to concentrate supplementation of high-producing dairy cows grazing at two pasture allowances. *J. Dairy Sci.* 85:1777–1792.
- Berry, D. P., L. Shalloo, A. R. Cromie, R. F. Veerkamp, P. Dillon, P. R. Am, J. F. Kearney, R. D. Evans, and B. Wickham. 2007. The economic breeding index: A generation on. Technical report to the Irish Cattle Breeding Federation.
- Binnie, R. C., D. J. Kilpatrick, and D. M. B. Chestnut. 1997. Effect of altering the length of regrowth interval in early, mid and late season on the productivity of grass swards. *J. Agric. Sci. (Camb.)* 128:303–309.
- Bircham, J. S., and J. Hodgson. 1983. The Influence of sward condition on rates of herbage growth and senescence in mixed swards under continuous stocking management. *Grass Forage Sci.* 38:323–331.
- Coffey, M. P., G. Simm, and S. Botherstone. 2002. Energy balance profiles for the first 3 lactations of dairy cows estimated using random regression. *J. Dairy Sci.* 85:2669–2678.
- Coleman, J., K. M. Pierce, D. P. Berry, A. Brennan, and B. Horan. 2009. The influence of genetic selection and feed system on the reproductive performance of spring-calving dairy cows within future pasture-based production systems. *J. Dairy Sci.* 92:5258–5269.
- Dillon, P., D. P. Berry, R. D. Evans, F. Buckley, and B. Horan. 2006. Consequences of genetic selection for increased milk production in European seasonal pasture based systems of milk production. *Livest. Sci.* 99:141–158.
- Dillon, P., T. Hennessy, L. Shalloo, F. Thorne, and B. Horan. 2008. Future outlook for the Irish dairy industry: A study of international competitiveness, influence of international trade reform and requirement for change. *Int. J. Dairy Technol.* 61:16–29.
- Dillon, P., J. R. Roche, L. Shalloo, and B. Horan. 2005. Optimising financial return from grazing in temperate pastures. Pages 131–147 in *Utilization of Grazed Grass in Temporal Animal Systems*. J. J. Murphy, ed. Wageningen Acad. Publ., Wageningen, the Netherlands.
- Edmonson, A. J., I. J. Lean, L. D. Weaver, T. Farver, and G. Webster. 1989. A body condition scoring chart for Holstein dairy cows. *J. Dairy Sci.* 72:68–78.
- Fulkerson, W. J., T. M. Davison, S. C. Garcia, G. Hough, M. E. Goddard, R. Dobos, and M. Blockey. 2008. Holstein-Friesian dairy cows under a predominantly grazing system: Interaction between genotype and environment. *J. Dairy Sci.* 91:826–839.
- Gilmour, A. R., B. R. Cullis, S. J. Welham, and R. Thompson. 2001. ASREML Reference Manual. New South Wales Agriculture, Orange Agricultural Institute, Orange, NSW, Australia.
- Harris, B., J. E. Pryce, and W. A. Montgomerie. 1996. Experiences from breeding for economic efficiency in dairy cattle in New Zealand. *Proc. Assoc. Advmt. Anim. Breed. Genet.* 17:434–444.
- Holmes, C. W., I. M. Brookes, D. J. Garrick, D. D. S. Mackenzie, T. J. Parkinson, and G. F. Wilson. 2002. *Milk Production from Pasture: Principles and Practices*. Massey University, Palmerston North, New Zealand.
- Horan, B., P. Dillon, P. F. Averdin, L. Delaby, F. Buckley, and M. Rath. 2005b. The interaction of strain of Holstein-Friesian cows and pasture-based feed systems on milk yield, body weight and body condition score. *J. Dairy Sci.* 88:1231–1243.
- Horan, B., P. Dillon, D. P. Berry, P. O'Connor, and M. Rath. 2005a. The effect of strain of Holstein-Friesian, feeding system and parity on lactation curves characteristics of spring calving dairy cows. *Livest. Prod. Sci.* 95:231–241.
- ICBF (Irish Cattle Breeding Federation). 2008. Irish cattle breeding statistics 2008. Irish Cattle Breeding Society Ltd., Shinagh House, Bandon. Co. Cork, Ireland.

- Journet, M., and C. Demarquilly. 1979. Grazing. Pages 295–321 in *Feeding Strategy for the High-Yielding Cow*. W. H. Broster and H. Swan, ed. Granada, London, UK.
- Kellaway, R., and S. Porta. 1993. Feeding concentrates supplements for dairy cows. Dairy. Res. Dev. Corp., Melbourne, Australia.
- Kennedy, J., P. Dillon, P. Faverdin, L. Delaby, F. Buckley, and M. Rath. 2002. The influence of cow genetic merit for milk production on response to level of concentrate supplementation in a grass-based system. *Anim. Sci.* 75:433–445.
- Le Du, Y. L. P., R. D. Baker, and R. D. Newberry. 1981. Herbage intake and milk production by grazing dairy cows. 3. The effect of grazing severity under continuous stocking. *Grass Forage Sci.* 36:307–318.
- Leaver, J. D. 1985. Milk production from grazed temperate grassland. *J. Dairy Res.* 52:313–344.
- Lee, J. M., D. J. Donaghy, and J. R. Roche. 2008. Effect of defoliation severity on regrowth and nutritive value of perennial ryegrass dominant swards. *Agron. J.* 100:308–314.
- Lips, M., and P. Rieder. 2005. Abolition of raw milk quota in the European Union: A CGE analysis at the member country level. *J. Agric. Econ.* 56:1–17.
- Macdonald, K. A., J. W. Penno, J. A. S. Lancaster, and J. R. Roche. 2008. Effect of stocking rate on pasture production, milk production and reproduction of dairy cows in pasture-based systems. *J. Dairy Sci.* 91:2151–2163.
- McCarthy, S., D. P. Berry, P. Dillon, M. Rath, and B. Horan. 2007. Influence of Holstein-Friesian strain and feed system on body weight and body condition score lactation profiles. *J. Dairy Sci.* 90:1859–1869.
- McEvoy, M., M. O'Donovan, E. Kennedy, J. P. Murphy, L. Delaby, and T. M. Boland. 2009. Effect of pregrazing herbage mass and pasture allowance on the lactation performance of Holstein-Friesian dairy cows. *J. Dairy Sci.* 92:414–422.
- Meijs, J. A. S., and J. A. Hoekstra. 1984. Concentrate supplementation of grazing dairy cows. 1. Effect of concentrate intake and herbage allowance on herbage intake. *Grass Forage Sci.* 39:59–66.
- O'Donovan, M. 2000. The relationship between the performance of dairy cows and grassland management on intensive dairy farms in Ireland. PhD thesis. University College Dublin, Ireland.
- Penno, J. 1999. Stocking rate for optimum profit. *South Island Dairy Event* 1:25–43.
- Philpott, B. 1995. New Zealand aggregate and sectoral productivity growth 1960–95. RPEP Paper 274. Victoria University, Wellington, New Zealand.
- Pryce, J. E., B. L. Harris, W. A. Montgomerie, R. Jackson, K. A. MacDonald, C. B. Glassey, B. S. Thorrold, and C. W. Holmes. 2005. Comparing feed allowances to inferred energy intake using data from a dairy grazing farm trial. *Proc. NZ Soc. Anim. Prod.* 65:225–230.
- Reed, K. F. M. 1978. The effect of season of growth on the feeding value of pasture. *J. Brit. Grassl. Soc.* 33:227–234.
- Roche, J. R., D. P. Berry, and E. S. Kolver. 2006. Holstein Friesian strain and feed effects on milk production, body weight and body condition score profiles in grazing dairy cows. *J. Dairy Sci.* 89:3532–3543.
- Ryan, W., D. Hennessy, L. Shalloo, J. Murphy, and T. Boland. 2010. Farm systems N balances for contrasting intensive grassland dairy production systems. In *Proc. British Society of Animal Science and the Agricultural Research Forum*, April 2010. Cambridge University Press, Cambridge, UK.
- Shalloo, L., J. Kennedy, M. Wallace, M. Rath, and P. Dillon. 2004. The economic impact of cow genetic potential for milk production and concentrate supplementation level on the profitability of pasture based systems under different EU milk quota scenarios. *J. Agric. Sci.* 142:357–369.
- SAS Institute. 2006. Users Guide: Statistics. Version 9.1. SAS Institute, Cary, NC.
- Tyrrell, H. F., and J. T. Reid. 1965. Prediction of the energy value of cows' milk. *J. Dairy Sci.* 48:1215–1223.
- Ulyatt, M. J. 1981. The feeding value of temperate pasture. Pages 125–141 in *Grazing Animals*. F. H. W. Morley, ed. Elsevier Publishing Co., Amsterdam, the Netherlands.
- Wheeler, L. J., and J. L. Corbett. 1989. Criteria for breeding forages of improved feeding value: Results of a Delphi survey. *Grass Forage Sci.* 44:77–83.
- Wilmink, J. B. M. 1987. Adjustment of lactation yield for age at calving in relation to level of production. *Livest. Prod. Sci.* 16:321–334.