The Impact of Somatotropin, Milking Frequency, and Photoperiod on Dairy Farm Nutrient Flows[1]

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ABSTRACT

Three technologies that increase milk production per cow and that are available to dairy producers are bovine somatotropin, three times daily milking, and extended daily photoperiod. Dairy herds fed according to National Research Council requirements were simulated to predict the impact of these technologies on N losses to manure and to water resources. Because Dairy Herd Improvement Association total lactation records (n = 93,080) revealed a positive linear relationship between 305-d milk production and calving interval, calving intervals were predicted to increase with the use of technologies and to result in a change in the ratio of lactating cows to growing heifers in a herd. Compared with a herd using no technologies, the use of bovine somatotropin, three times daily milking, or extended photoperiod were predicted to reduce herd N excretion per unit of milk by 7.8, 7.0, and 3.6%, respectively. When the use of all three technologies was simulated, N losses to manure were decreased by 15.7% when assuming calving interval increases from the technologies or 15.4% without accounting for calving interval increases. Reductions in feed N requirements and manure N losses with these three technologies were predicted to reduce environmental N loading by up to 16%.
(**Key words:** bovine somatotropin, milking frequency, photoperiod, nitrogen efficiency)

Abbreviation key: 3X = three times daily milking, **LDPP** = long daily photoperiod.

INTRODUCTION

Nitrogen originating from dairy farms can accumulate in the land, air, and water, where it has potentially negative environmental effects. In the land and water, N accumulation disrupts ecosystem nutrient balance (10). In the air, volatile nitrogen oxides have been blamed for ozone loss and global warming, and volatile ammonia contributes to acid rain (11, 21, 23). Improved animal management has a greater potential than improved crop or manure management to reduce total N losses from dairy farms (13). Aspects of animal management include the range of short- and long-term decisions made by herd managers, such as diet formulation, reproductive practices, animal housing, and health management.

The amount of milk produced in any geographical area is primarily driven by market demand and by the profitability of dairy farming. Cow management strategies that reduce total environmental N losses while meeting market demand for milk are likely to be the most sustainable. Strategies that increase animal N efficiency (N in product/N intake) will reduce total N fed to cows and total N excreted from cows to supply a given quantity of milk. If the milk market is filled by more efficient cows, total nutrient losses resulting from the production of that amount of milk will be reduced. One way to increase nutrient utilization efficiency of cows is to increase production per cow to dilute maintenance requirements, and thus reduce the total number of cows required to meet the market demand for milk.

Three technologies that increase milk production per cow are injections of bST, three times daily milking (**3X**) instead of twice daily milking, and a long daily photoperiod (**LDPP**) accomplished through artificial lighting. These technologies are predicted to increase the productive efficiency of dairy cows by diluting nutrient intake requirements per unit of milk (1, 25). If producers adopt any of these technologies into their dairy cow management systems, more efficient cows are used to fill the market demand for milk. More efficient cows require less feed per unit of milk produced. If the milk market is filled by more efficient cows, the total crop and fertilizer requirements necessary to fill this market will be reduced. Also, because 50 to 75% of total manure N is lost to air and water (13, 26), reduced manure production by more efficient cows should lower environmental N loading. The use of tech-

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Table 1. DHIA data used in simulations.

Variable	Source[1]	N	Mean	SD
305-day 3.5% FCM, kg	2	166,960	8957	1877
DIM	1	73,465	159	92
Dry period, d	2	201,497	62.3	21.4
Milk, primiparous cows, kg/d	1	24,467	28.7	8.3
Milk, second lactation cows, kg/d	1	20,172	33.1	10.9
Milk, multiparous cows, kg/d	1	28,826	34.4	11.6
Milk fat, %	1	73,465	3.55	0.79
Age at first calving, mo[2]	2	110,792	25.9	2.50
Calving interval, mo	2	194,569	13.2	2.11
Weight, primiparous cows, kg[3]	2	109,241	536	38.9
Weight, second lactation cows, kg[3]	2	82,802	582	51.8
Weight, multiparous cows, kg[3]	2	127,404	616	67.3

[1] Source 1 = Lancaster DHIA test-day production records collected between July 1996 and April 1998. Source 2 = Lancaster DHIA total lactation records collected between June 1977 and November 1997.

[2] Age at calving calculated from birth dates and calving dates in records.

[3] Parity predicted by age at calving. Primiparous cows were assumed to be all cows below 34 mo of age at calving, and second lactation cows were assumed to be between 34 and 48 mo of age at calving. Cows greater than 48 mo of age at calving were predicted to be in their third or later lactation.

nologies to increase milk production should, therefore, reduce environmental N loading required to fill the market demand for milk.

The objectives of this simulation were 1) to predict daily milk production, N and P intake, and N excretion of a typical dairy herd, 2) to simulate effects of bST, 3X, LDPP, or any combination of these treatments on predicted herd milk production and N and P flows, and 3) to predict the number of cows and nutrient flows required by each of the simulated herds to fill a theoretical market demand of 100,000 kg of milk per day.

MATERIALS AND METHODS

Parameterization of the Base Herd

Production parameters for a simulated base herd were developed from Lancaster (PA) DHIA records (Table 1). The first of these records were collected between July 1996 and April 1998. These data consisted of test-day milk production, milk fat, parity information, and DIM for individual lactating cows from 705 dairy herds that reported at least once during that period. Production data from all cows fewer than 342 DIM (see below) in the data set were modeled to fit parameters to Wood's equation, which describes changes in milk production (kg/d) or composition (fat %) as a lactation progresses (27):

$$\ln (y) = a + b * \ln (n) - c * n$$

where y = milk production (kg/d) or milk fat (%), n = weeks in milk, and a, b, and c are constants determined by fitting the DHIA data to this equation. Values for a, b, and c were fit separately for primiparous cows, second lactation cows, and third or later lactation cows (Table 2). Because milk yield observations for cows at above-average DIM flatten and extend the lactation curves, only cow observations below 342 DIM (the predicted lactation length for the base herd) were used to parameterize production curves.

Total lactation records (n = 319,447) were also used to calculate parameters of the base herd (Table 1). This data set, however, did not report parity, so parity was estimated from cow age. Cows less than 34 mo of age at calving were assumed to be primiparous. Cows between 34 and 48 mo of age at calving were assumed to be second lactation cows, and those greater than 48 mo of age at calving were assumed to be in their third or later lactation. A sensitivity analysis revealed that changing these age ranges by 2 mo changed predicted BW of each parity group only slightly, by a maximum of 7 kg. The resulting BW were 536 kg (SD = 39 kg) for primiparous cows, 582 kg (SD = 52 kg) for second lactation cows, and 616 kg (SD = 67 kg) for third or later lactation cows. Aside from using BW differences, the NRC does not account for breed differences in predicting nutrient requirements for lactating cows. Average BW taken from the DHIA data were assumed to reflect an average cow across breeds. Age at calving was calculated by subtracting each cow's calving date from her birth date. Calculated ages at calving that were below 18 mo were excluded, and ages greater than 3 SD above the mean age were also excluded. The resulting average age at first calving was 25.9 mo (SD = 2.5 mo). The average dry period was calculated by excluding observations of 0 d or greater than 3 SD above the mean. The average dry period length was 62 d (SD = 21 d).

Simulation of Technology Use by the Base Herd

After the milk production and herd characteristics of a base herd were developed, the effects of bST, 3X, LDPP, or any combination of these technologies on base herd characteristics were simulated. Changes in milk yield or composition due to treatment were assumed to be fixed responses as kilogram per day for yield or as additive changes in milk fat percent (7). Biweekly injections of bST beginning at 70 DIM were predicted to increase milk production by 4.2 kg/d for primiparous cows and by 5.5 kg/d for multiparous cows (22). Injections of bST were assumed to have no effect on milk

Table 2. Parameters from DHIA data modeled to fit Wood's equation.[1]

	Lactation 1		Lactation 2		Lactation 3+	
Parameter	Milk	Fat	Milk	Fat	Milk	Fat
a	3.13	1.34	3.33	1.33	3.35	1.38
b	0.181	–0.102	0.245	–0.112	0.284	–0.131
c	–0.0146	0.0084	–0.0256	0.0099	–0.0302	0.0102
R^2	0.085	0.052	0.227	0.064	0.283	0.064

[1] ln (y) = a + b * ln (n) – c * n where y = milk production (kg/d), milk fat (%), or milk protein (%) and n = weeks in milk. Values derived from Lancaster, DHIA test-day records collected between July 1996 and April 1998 (n = 77,406).

fat content (1, 19, 22). Increasing milking frequency from twice daily to three times daily was predicted to increase daily milk production of primiparous cows by 3.3 kg and multiparous cows by 3.5 kg (7). Three times daily milking reduced milk fat percentage by 0.07 and 0.17 and milk protein percentage by 0.1 and 0.12 for first lactation cows or multiparous cows, respectively (19). However, in accordance with the NRC (16) model that was used for the simulation, the changes in milk protein percentage with 3X milking were predicted from these changes in fat percentage. Extended daily photoperiod of 16 h light and 8 h dark was predicted to increase milk production for at least 9 mo of the year (5, 17). For three-fourths of the year, therefore, LDPP was predicted to increase milk production by about 8%, 2.2 kg/d for primiparous cows and 2.6 kg/d for other cows (4). Long daily photoperiod was assumed to have no effect on milk composition (6). Milk responses to technologies were simulated as an increase in milk or a change in milk fat relative to the base herd using none of the technologies. All treatment combinations were assumed to be additive because of the observed additivity of bST and 3X responses (7) and of bST and LDPP responses (14). The predicted production responses were used to refit the Wood's curve to predict 305-d 3.5% FCM yields for primiparous, second lactation, or third or later lactation cows using each treatment or treatment combination (Figure 1).

Analysis of the test-day Lancaster DHIA records revealed that, on average, 34% of cows in a herd were primiparous, 27% were in their second lactation, and 39% were in their third or later lactation. Parity within simulated herds was assigned accordingly. Daily 3.5% FCM for each cow was calculated as (24):

$$3.5\%\ \text{FCM (kg)} = \text{milk (kg)} * (44.01 * [\%\ \text{fat}] + 163.56)/317.60.$$

Herd average 305-d 3.5% FCM production for each treatment combination was estimated by summing the predicted 305-d yields of each parity group and then by multiplying that sum by the fraction of cows in that parity group. Because calving interval has been found to increase with 305-d milk production (2, 8), the DHIA data set consisting of 340,708 total lactation records collected between June 1977 and November 1997 was used to assess this relationship. The mean calving interval in this dataset was 13.3 mo (SD = 2.53 mo) and the mean 305-d 3.5% FCM production was 8959 kg (SD = 1935 kg). A regression analysis in SAS (18) revealed a significant positive linear relationship between calving interval and 305-d 3.5% FCM production (Figure 2). This relationship was used to estimate calving interval for each of the simulated herds based on milk production. The predicted calving interval for the base herd was 404 d.

The predicted calving interval for each treatment and the assumption that all simulated herds contained 1000 mature (lactating and dry) cows and enough growing heifers to sustain the herd were used to further predict herd distribution. As stated previously, dry period length was predicted to be 62 d for all herds, so the average number of cows in each herd was calculated as:

$$\text{dry cows (n)} = (62\ \text{d dry/calving interval in days}) * 1000\ \text{primiparous and multiparous cows}$$
$$\text{lactating cows (n)} = 1000 - (\text{number of dry cows})$$

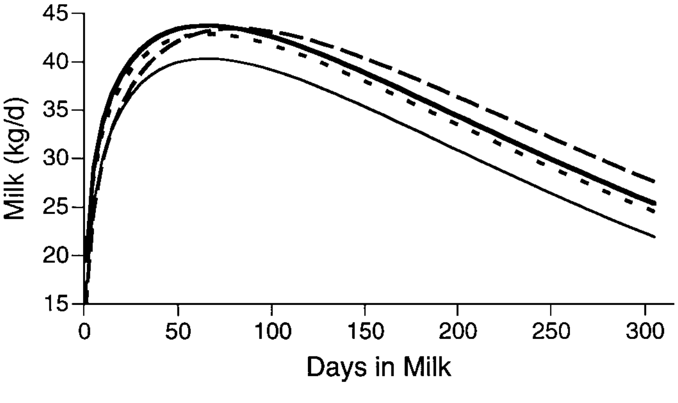

Figure 1. Predicted milk production by DIM for an average multiparous cow from the base herd (——), a herd using bST (■ ■ ■), a herd using three times daily milking (__), or a herd using long daily photoperiod (- - -).

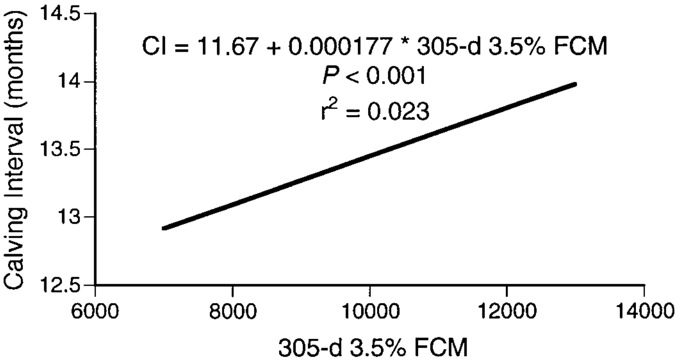

Figure 2. Linear regression of calving interval (CI) in months by 305-d 3.5% FCM production. Data from Lancaster DHIA total lactation records collected between June 1977 and November 1997 (n = 93,080).

Calf birth rate was estimated by the following:

calves born per year (n) = (1000 primiparous and multiparous cows) * 365 d year^{-1}/treatment calving interval in days

Birth of calves was assumed to be spread evenly throughout the year, and 6.6% of calves were assumed to be born dead (15). Of the live births, 50% were assumed to be females and retained in the herd as possible replacements. Of the female calves born alive, an additional 10.8% were predicted to die before weaning at 60.9 d of age (15). Replacement heifers were predicted to calve for the first time at 25.9 mo of age, the average age at first calving among the herds reporting to the Lancaster DHIA. Losses (culling and death) of replacements were evenly distributed between weaning and 25.9 mo of age to allow enough heifers to enter the milking herd each calving interval to keep the primiparous cow fraction of the herd at 34%. Heifer birth weight was assumed to be 41 kg, and growth of heifers was 683 g/d to 100 d of age, 745 g/d from 100 d of age to 1 yr, and 603 g/d from 1 year to calving (9).

Mature cows were predicted to milk from calving until 62 d (the average dry period) before the subsequent calving. Variation in milk production among the lactating cows was simulated because the Wood's equation estimates average production of a cow without accounting for individual variation (27). Analysis of the test-day Lancaster DHIA records revealed that a standard deviation of 8.4 kg of milk per day was the average within-herd variation in milk production. This was reduced to 6.9 kg milk/d after accounting for cow differences in DIM and in parity. Random numbers (mean = 0, SD = 6.9) were, therefore, added to individual milk production values predicted by the Wood's curves to simulate observed phenotypic variation (see Figure 3).

Each of the simulated herds was divided into groups for feeding, and protein requirements were predicted by the NRC (16). The lactating cows from each simulated herd were divided into three equally sized groups based on predicted protein requirements as a fraction of DMI. Dry cows were fed as one group. Growing heifers were divided based on age into an individually fed group (birth to age 100 d), two growing groups (age 100 to 300 d and age 300 to 460 d), one breeding group (age 460 to 505 d), one pregnant group (age 505 to 715 d), and one fresh group (age 715 to 787 d). For all groups of mature or growing cows, mean requirements for RDP and RUP as a percentage of DMI were predicted by NRC (16), and protein offered in the ration was 1 SD above the mean requirements so that most cows would be fed adequately to maintain production. Dry matter intake for individual cows was predicted by NRC (16), and individual intake of protein was calculated by multiplying the protein content of the diet by the predicted DMI of each cow. When predicted dietary protein intake of individual cows or heifers was inadequate to meet NRC (16) requirements for milk production or growth, milk yield (12) or growth rates were reduced to levels satisfied by the diet. When milk losses were predicted, these new and lower individual milk productions were used to predict new protein requirements and DMI from the NRC. Feeding was simulated at the initial dietary concentrations of RDP and RUP fed to each cow's group, but the new milk production, protein requirements, and DMI were used to predict further milk losses. This itera-

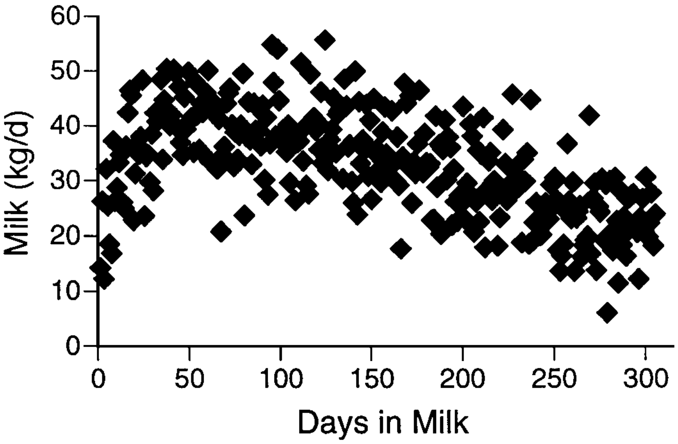

Figure 3. Variability in milk production by DIM for individual multiparous cows in the simulated base herd. Lancaster DHIA records for third or later lactation cows were used to fit Wood's curve (27) to predict milk production by DIM. Random variation (SD = 6.9 kg/d) in milk production was added to simulate observed production differences between multiparous cows that are not due to differences in DIM or parity.

tive process was repeated 20 times for each herd, at which point additional predicted milk losses were minimal. Use of this iterative process resulted in reduced herd milk yields compared with the initial milk production predicted for each herd. In these simulations, initial herd milk productions before the iterations were, therefore, the theoretical maximum amounts of milk that would be produced if all cows in each herd consumed adequate protein. Because actual, but not potential, growth of heifers is reported in the literature, potential growths of 881 g/d for 100 d to 1 yr of age and of 669 g/d from 1 yr until calving were used. After 20 iterations were performed, the predicted actual growth was the same as the 745 and 603 g/d for the younger and older heifers, respectively, that was calculated from Heinrichs and Hargrove (9). Urinary and fecal protein were calculated for individual cows and heifers based on NRC predictions (16).

When the ration of individual dry cows was predicted to contain inadequate protein, estimated urinary N excretion was reduced. For individual cows or heifers, whenever intake of dietary protein was predicted to be above requirements, all of the additional RDP and 80% of the additional RUP were added to NRC predicted urinary protein, and the remaining 20% of extra RUP was added to NRC predicted fecal protein (16). Estimates of whole herd N flows were determined by summing the predicted N intakes and excretions of all growing heifers and lactating and dry cows in each herd. Nitrogen efficiencies ([intake N − excreted N]/intake N) for the lactating cows and for the herds were also predicted. Phosphorus feeding was simulated at each group's average P requirement because bone reserves of minerals are thought to buffer the effects of short-term underfeeding or overfeeding to obviate the need to exactly match requirements throughout lactation.

Predicted manure N losses to water were based on the assumption that 50 to 75% of manure N is volatilized or runs off before becoming available to crops (13). The feeds used on the farm were predicted to consist of 75% nonlegumes and 25% legumes. Nonlegumes were predicted to have an apparent uptake of manure N ranging from 50 to 75%, and the apparent N uptake of legumes was assumed to be 90% (13).

Because the relationship between milk production and calving interval is weak ($r^2 = 0.023$), the simulations were repeated assuming no changes in calving interval and herd distribution with technologies. In these simulations, characteristics of the base herd using no treatments were assumed to remain constant with the use of bST, 3X, and LDPP.

RESULTS AND DISCUSSION

Lactation Curves

The Wood's lactation curves for an average multiparous cow from the base, bST, 3X, and LDPP herds are displayed in Figure 1. For a multiparous cow in the base herd, milk production was predicted to rise rapidly following calving and to peak at 40.4 kg/d about 66 d after calving. The use of either 3X or LDPP was predicted to increase the magnitude of milk production without changing the general shape of the lactation curve. Injections of bST beginning at 70 DIM, however, were predicted to affect the lactation curve by extending the rise to peak production that occurred at 81 DIM and 43.6 kg/d. Also, the decline in milk production following the peak was the most gradual in the bST herd, so higher levels of milk production were predicted to be sustained throughout the rest of the lactation. This improved persistency has been observed in one study (1), but not in another (22).

Because the impact of technologies on milk production was assumed to be additive, treatment combinations were simulated by adding the magnitudes of response to individual treatments relative to the base herd. Simulation of individual milk production variation for cows on each treatment reflected observed phenotypic variation among cows without affecting the mean milk yield of each treatment herd (Figure 3).

Herd Distribution

Characteristics of herds using any combination of bST, 3X, or LDPP are displayed in Table 3. The simulated base herd not using any of the technologies was predicted to have a 305-d 3.5% FCM production of 9328 kg. Predicted calving interval was 405 d, and that corresponded to 846 milking cows, 154 dry cows, and 731 growing heifers in this herd of 1000 mature cows. The use of one technology, on average, was predicted to increase 305-d 3.5% FCM production by 925 kg to 10,253 kg. The simulated calving interval increased to 410 d, and the herd was composed of 848 milking cows, 152 dry cows, and 723 growing heifers. Similarly, the use of any two or all three technologies in combination was predicted to increase 305-d 3.5% FCM to an average of 11,165 kg and 12,064 kg, respectively. The predicted calving interval for a herd using two technologies averaged 415 d, and it was 420 d for the herd using all three technologies. Consequently, cow distribution for a herd using two technologies was an average of 850 lactating cows, 150 dry cows, and 715 growing heifers. The herd using all three technologies was predicted to have 852 milking cows, 148 dry cows, and 707 growing heifers.

In general, the use of technology was predicted to increase milk production, and increased milk production tends to extend the calving interval (8). Calving intervals might be delayed when high production postpones the return to reproductive competence or when it becomes profitable for farmers to extend the milking

Table 3. Herd characteristics and distribution.

Treatment[1]	Base[2]	bST	3X	LDPP	bST + 3X	bST + LDPP	3X + LDPP	bST + 3X + LDPP
305-d milk, kg[3]	9328	10,513	10,167	10,078	11,329	11,263	10,903	12,064
Calving interval, d[4]	405	412	410	409	416	416	414	420
Milking cows, n	846	849	848	848	850	850	849	852
Dry cows, n	154	151	152	152	150	150	151	148
Growing heifers, n	731	720	723	726	712	715	718	707

[1] Treatments were no treatment (Base), bST, three times daily milking (3X), or long daily photoperiod (LDPP). Treatment combinations are indicated by a (+).

[2] Base herd parameters were derived from Lancaster DHIA test-day production records collected between July 1996 and April 1998 (n = 77,406) and from Lancaster DHIA total lactation records collected between June 1977 and November 1997 (n = 93,080 for 305-d 3.5% FCM and calving interval, n = 201,497 for days dry, n = 110,792 for age at first calving).

[3] Milk weights are in 3.5% FCM calculated from (152).

[4] Calving interval estimated from an observed linear relationship.

period for higher producing cows (2, 8). An extended calving interval can also increase the percentage of lactating cows on a farm as cows spend proportionately more time lactating. As calving intervals are lengthened, calves tend to be born less frequently and fewer replacement heifers might be needed per year, resulting in fewer total heifers. Farm management, however, plays a critical role in determining calving interval and cow distribution. Because of the weak relationship between milk production and calving interval ($r^2 = 0.023$), simulations of farm N flows and N efficiency were repeated assuming no changes in herd distribution caused by changes in milk production. In these simulations, the calving interval and herd distribution predicted for the base herd were assumed to remain constant with the use of technologies.

Lactating Cows

The predicted impact of the use of bST, 3X, and LDPP on milk production and N utilization in the lactating cows is presented in Table 4. For the base herd using none of these technologies, the average milk production was predicted to be 29.1 kg/d. Predicted daily N intake was 470 g, and daily N excretion was 313 g. Consequently, lactating cows from this herd were predicted to have a N efficiency of 33.4%. On average, the milk production from a herd using one technology was increased by about 2.9 kg to 32.0 kg/d. This was accomplished through a total N intake of 502 g/d and a total N excretion of 330 g/d. Nitrogen efficiency of lactating cows using bST, 3X, or LDPP was increased to an average of 34.2%. Similarly, the use of two technologies simultaneously was predicted to increase average milk production to 35.0 kg/d. Nitrogen intake increased to 532 g/d, and N excretion was 346 g/d, resulting in an N efficiency of 35.0%. The application of all three technologies at once was predicted to increase milk production to 37.9 kg/d, N intake to 562 g/d, and N excretion to 362 g/d. Nitrogen efficiency of a cow using bST, 3X, and LDPP was estimated to be 35.7%, a 6.9% increase over the 33.4% efficiency predicted for the base herd.

The predicted improvements in lactation N efficiency with the use of technologies were primarily a result of maintenance dilution (1). As lactating cows produce more milk, intake is predicted to increase, driving up

Table 4. Characteristics of the average lactating cow from each treatment.[1]

Treatment[2]	Base[3]	bST	3X	LDPP	bST + 3X	bST + LDPP	3X + LDPP	bST + 3X + LDPP
Milk, kg/d	29.1	33.0	32.3	30.8	36.2	34.7	34.0	37.9
N intake, g/d	470	515	500	490	543	534	519	562
N excretion, g/d	313	337	329	324	352	347	339	362
N efficiency, %	33.4	34.6	34.2	33.9	35.3	35.0	34.7	35.7

[1] A linear change in calving interval with increasing milk production was simulated.

[2] Treatments were no treatment (Base), bST, three times daily milking (3X), or long daily photoperiod (LDPP). Treatment combinations are indicated by a (+).

[3] Base herd parameters were derived from Lancaster DHIA test-day production records collected between July 1996 and April 1998 (n = 77,406) and from Lancaster DHIA total lactation records collected between June 1977 and November 1997 (n = 93,080 for 305-d 3.5% FCM and calving interval, n = 201,497 for days dry, n = 110,792 for age at first calving, n = 319,447 for BW).

their maintenance requirements for metabolic fecal N because metabolic N is linked to feed intake in the current NRC (16). Maintenance requirements for P are predicted to stay the same despite changes in milk yield, reducing P requirements per unit of milk as production increases (16). This effect, however, is an artifact of NRC predicting metabolic fecal P requirements based on BW instead of P intake (16). As with N, maintenance P requirements do appear to increase with higher P intake (20). Despite these effects, the increase in N and P maintenance requirements with higher production are not as great as the increase in the allocation of intake N and P to milk (16, 20). As a consequence of this maintenance dilution, increases in milk production with the use of technologies are predicted to direct relatively more of ingested N and P to milk and relatively less to excretion, improving animal efficiency. This effect has been noted in research trials involving both bST and LDPP (1, 4). These technologies, therefore, stimulate a proportionately greater increase in milk production than in nutrient requirements or manure production, potentially increasing nutrient utilization efficiency.

Whole Herd Nutrient Flows

The predicted changes in whole herd N efficiency with the use of technologies are illustrated in Figure 4. When calving interval changes were simulated, bST use was predicted to increase N efficiency of the entire herd by about 4.7%. Similarly, the use of 3X or LDPP resulted in 3.2 and 2.1% higher N efficiencies, respectively. The use of two or three technologies in combination was predicted to result in an average increase in N efficiency of 6.3 and 9.1%, respectively. This predicted improvement in herd N efficiency arose from two sources. The first is the improved N utilization efficiency of the lactating cows, affecting the N balance of the entire herd. The second results from changes in herd distribution when milk production increases were predicted to prolong the lactation cycle. Longer periods of lactation were predicted to reduce the numbers of heifers and dry cows in a herd at any time. Because these groups use intake N quite inefficiently compared with the lactating cows (16), a reduction in the fraction of dry cows and heifers in a herd caused an increase in predicted herd N efficiency.

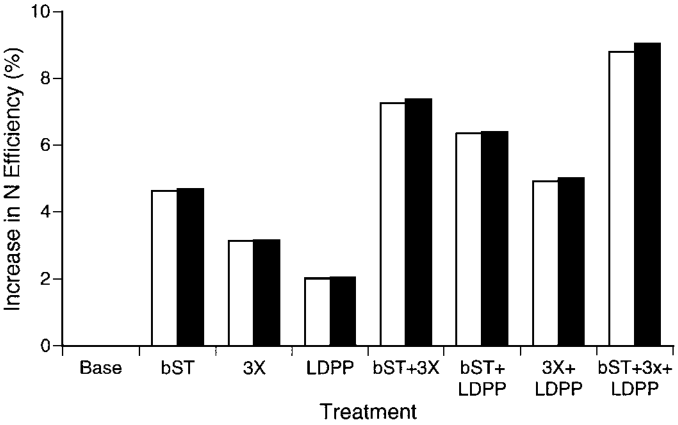

Figure 4. Predicted impact of the individual or combined (+) use of bovine somatotropin (bST), three times daily milking (3X), and long daily photoperiod (LDPP) on whole-herd N utilization efficiency relative to the base herd. Results calculated assuming that technology does (■) or does not (□) increase calving interval.

When no changes in calving interval and herd distribution due to milk production were simulated, improvements in whole herd N efficiency were strictly due to predicted increases in productive efficiencies of the lactating cows. In these simulations, the use of bST, 3X, or LDPP alone was predicted to increase herd N efficiency by 4.6, 3.2, and 2.1%, respectively. The use of two technologies in combination was predicted to increase N efficiency by an average of 6.2%, and the use of all three technologies was predicted to increase N efficiency by 8.9%. Assuming that calving interval was unaffected by technologies reduced the predicted improvement in herd efficiency with the use of technologies only slightly (< 5%).

Resources required by the simulated herds to satisfy a theoretical market demand of 100,000 kg of milk/d are listed in Table 5. When no technologies were used, the predicted number of mature cows required to fill this demand was 4067. This number of cows was predicted to consume 2099 kg/d of N and to excrete 1496 kg/d of N, resulting in a N efficiency of 28.7%. When calving interval changes with technologies were simulated, the use of one technology was predicted to reduce the number of cows by 9.4% to 3685, N intake was reduced to 1997 kg/d, and N excretion was reduced to 1405 kg/d. Consequently, herd N efficiency was predicted to increase to 29.7%. The use of two technologies was predicted to further decrease the number of cows to 3368, and N efficiency was predicted to increase to 30.5%. Using bST, 3X, and LDPP in combination to produce 100,000 kg/d of milk was predicted to require 3098 cows, a 24% reduction in number of cow. This simulated herd consumed 1837 kg/d of intake N, excreted 1263 kg N/d and had a predicted N efficiency of 31.3%. Similar improvements in N efficiency with the use of technologies were predicted when no changes in calving interval were simulated, although the magnitudes of predicted responses were slightly reduced (< 1%).

Nitrogen losses to water resources were predicted to be 1135 kg/d for the base herd. Losses were reduced to

Table 5. Predicted characteristics of herds producing 100,000 kg of milk/d.

Treatment[1]	Base[2]	bST	3X	LDPP	bST + 3X	bST + LDPP	3X + LDPP	bST + 3X + LDPP
Simulated with calving interval changes[3]								
Mature cows, n	4067	3566	3656	3834	3249	3389	3467	3098
Intake N, kg/d	2099	1973	1977	2041	1875	1929	1930	1837
Excreted N, kg/d	1496	1380	1392	1443	1297	1340	1348	1261
Herd N efficiency, %	28.7	30.1	29.6	29.3	30.8	30.6	30.2	31.3
N loss to water, kg/d[4]	1064	981	990	1026	922	952	958	896
Simulated without calving interval changes[5]								
Mature cows, n	4067	3565	3650	3831	3242	3383	3461	3091
Intake N, kg/d	2099	1976	1978	2042	1878	1932	1933	1843
Excreted N, kg/d	1496	1382	1392	1444	1300	1342	1351	1267
Herd N efficiency, %	28.7	30.0	29.6	29.3	30.8	30.5	30.1	31.2
N loss to water, kg/d	1064	982	990	1026	924	954	960	900

[1] Treatments were no treatment (Base), bST, three times daily milking (3X), or long daily photoperiod (LDPP). Treatment combinations are indicated by a (+).

[2] Base herd parameters were derived from Lancaster DHIA test-day production records collected between July 1996 and April 1998 (n = 77,406) and from Lancaster DHIA total lactation records collected between June 1977 and November 1997 (n = 93,080 for 305-d 3.5% FCM and calving interval, n = 201,497 for days dry, n = 110,792 for age at first calving, n = 319,447 for BW).

[3] Simulated with the assumption that increased milk production with the use of technology extends the calving interval and consequently reduces the proportion of dry cows and the number of growing heifers in the herd.

[4] Sixty-three percent of manure N was predicted to be lost by volatilization before manure application as fertilizer. Crop profile was 75% nonlegume and 25% legume. Assumed apparent uptake of manure N by nonlegumes was 63% and apparent uptake by legumes was 90%.

[5] Simulated with the assumption that the herd distribution predicted for the base herd was not altered with technology.

907 kg/d when assuming the best-case scenario of 50% manure N volatilization losses and 75% N uptake by nonlegume crops. Similarly, these losses increased to 1272 kg/d for the base herd when assuming the worst-case scenario of 75% manure N volatilization losses and 50% N uptake by nonlegumes. The use of one technology was predicted to reduce total N losses to water by 6.1% to about 999 kg/d (852 to 1195 kg/d) with or without simulating changes in calving interval. Two technologies were predicted to further decrease N losses by about 11.2% to 944 kg/d (807 to 1131 kg/d) and to 946 kg/d (810 to 1135 kg/d) for herds simulated with or without calving interval changes, respectively. On the average, the use of all three technologies was predicted to reduce N losses to water resources by 15.6% to about 898 kg/d (768 to 1077 kg/d).

The use of technologies is predicted to reduce the total number of cows and the total nutrient excretion required to fill the market demand for milk. Similarly, adoption of these technologies by American dairy farmers should decrease the total number of cows in the United States. A precedent for this predicted effect was a halving of the cow population that accompanied a doubling of individual cow milk production between the years of 1955 to 1980 (3). The dairy industry today, however, is moving towards larger herds. Although total cow population is predicted to decrease with the use of technologies, the number of cows on an average dairy may remain the same or even increase. As a consequence, total N and P excreted by a single herd can be expected to increase, resulting in a greater need of land for crop production and manure application. Otherwise, operating costs may increase because some manure nutrients may need to be exported off the farm to prevent N and P accumulation in farm soils.

A reduction in resources required to produce a given quantity of milk with the use of bST has previously been suggested and examined (1, 11). In a similar simulation study by Johnson et al. (11) examining the environmental impact of bST, adoption of bST by all dairy farmers was predicted to reduce cow numbers by 11% and N excretion by 8%. These results are similar to those in the present simulation in which cow numbers were reduced by 11.7% and N excretion was reduced by 7.6%. Furthermore, Johnson et al. (11) found that the use of bST should reduce cropland requirements by 6%, corresponding to a 5% reduction in soil losses. Also, irrigation water and fossil fuel requirements were reduced by 9 and 6%, respectively (11).

Effects of technologies on whole farm P intake were also simulated. When the base herd was fed at the average P requirement (16), the average whole farm P intake per kilogram of milk produced was 3.1 g. The use of one technology was predicted to reduce P intake, on average, by 4.0% to 3.0 g/kg of milk when calving interval changes were simulated. This value is lower than the 10% reduction predicted in (11) for the use of bST alone. The use of two technologies reduced P intake 8.0% relative to the base herd to 2.9 g/kg. All three technologies were predicted to reduce herd P intake to 2.8 g/kg of milk produced, 11.2% less than the base herd. Losses of P to the environment are, therefore, predicted to be reduced with the use of technologies.

CONCLUSIONS

Results of this simulation indicate that the application of bST, 3X, or LDPP to dairy herds has the potential to reduce nitrogen losses from a herd per unit of milk. Use of these technologies on the lactating cows is predicted to increase milk production and to subsequently increase the efficiency of conversion of intake nutrients to milk. Consequently, technologies should reduce cow numbers, feed nutrient consumption, manure production, and N losses to water resulting from the production of a given quantity of milk. When increased milk production with the use of technologies was predicted to increase calving intervals of the simulated herds, the magnitudes of predicted responses were somewhat greater. Regardless of the simulated impact on calving interval, the application of bST was predicted to have the greatest single positive impact on N efficiency. Similarly, when two technologies were simulated, the largest effect on N efficiency was predicted for the use of bST and 3X in combination. Overall, these simulations suggest that the use of technologies such as bST, 3X, and LDPP that increase animal production have the potential to reduce environmental loading of N while producing enough milk to meet the market demand.

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