ABSTRACT
Most dairy farms have the potential to increase profitability by improving the ration fed to the herd and the precision with which it is delivered. An integrated technology focused on improved feed conversion efficiency, the Keenan Mech-fiber system, is discussed as an opportunity to improve farm profitability, animal health and well-being, and environmental sustainability of dairy production. Margin gains averaging around $180 per cow annually have been achieved with French and United Kingdom herds within 1 yr of adopting the Keenan Mech-fiber system in each of the years from 2006 to 2009. Gains by herds in France were larger than those in the United Kingdom. The key performance indicator underlying these gains was feed conversion efficiency, whereby the same or a smaller amount of feed DMI generated greater yields of milk solids per cow. The gains were associated with large improvements in animal health and substantial decreases in greenhouse gases per unit of milk produced. The nutrition system generating these gains is applicable in all places where dairy cows are fed mixed rations.

Key words: animal health, cattle nutrition, feed conversion efficiency, greenhouse gas emissions, production economics

INTRODUCTION
The United States dairy industry has evolved under conditions of relative milk price stability and low feed prices with abundant land available for herd expansion. Competitive pressure to raise productivity has led to major changes typified by expansion and consolidation into larger units, the loss of many smaller herds, and a continued focus on high yields based on intensive feeding. The changes occurred within a regulatory policy with minimal regard for environmental consequences or regional comparative advantage. Although the United States industry as a whole has been hugely successful in meeting increased demand at low cost, individual farms have continued to face smaller economic margins and minimal profitability. Innovations to raise economic efficiency have been largely exhausted by the biggest and best farms, and new avenues must be found.

In many countries, the effect of dairy production on greenhouse gas (GHG) emissions is receiving increased attention. New Zealand’s dairy industry depends on global trading of dairy products and has committed to the challenge of finding ways to provide a cleaner and “greener” image for its dairy products (Clark et al., 2003). In the United Kingdom, agriculture contributes only 0.7% of gross domestic product yet is estimated to be responsible for 7% of national GHG emissions, with dairy cows and beef cattle providing a disproportionate share of the total (UK Cabinet Office, 2008). There are public concerns about the welfare and health of intensively farmed livestock. Although these concerns at present
may be more directed at the poultry and swine sectors, the dairy industry is not isolated from such scrutiny. With increased use of the Holstein breed, several issues have emerged that are thought to be related in part to consequences of limited trait selection, principally increased milk production. Compromised fertility, excessive body condition loss during early lactation, increased lameness and increased mastitis, lower milk solids, increased animal health issues, and decreased longevity have all been attributed in some way to the dominance of the Holstein breed (O’Callaghan et al., 1999).

On many farms operating in good facilities with excellent management, such issues are of limited importance and introduction of the higher yielding Holstein has been an unqualified success. In contrast, other dairy farms operating in out-dated facilities and with less competent management have contributed to some of the issues raised above, and in this respect poor nutritional practice is a major contributory factor. As highlighted by Cunningham (2005), “Genetics has created the potential, nutrition has failed to deliver that potential,” irrespective of the type of system practiced. Although in recent years actual milk yield has increased at a faster rate than the rate of genetic improvement in the United States (Cassell, 2001), some of this improvement has come from nutritional practices such as high grain feeding that may not maximize efficiency and may compromise animal health. Most dairy farmers understand the importance of good animal health and realize its dual implications for animal welfare and overall profitability.

The central focus of this paper is use of a technology that delivers better nutrition and increases economic margins of dairy production, while avoiding many of the health issues associated with high milk production and decreasing GHG output per unit of milk produced. Herd survey data are reported to support the large improvements gained through adoption of a unique nutrition technology system, the Keenan Mech-fiber (KMF) system (Richard Keenan & Co., Borris, County Carlow, Ireland). The paper first examines the economic scope for improving dairy cow nutrition and management and then provides a brief explanation of the key elements of good dairy cattle nutrition upon which the system is based. A brief description is included of the system as a fully integrated feeding program for delivering improved nutrition. The system has been widely applied in France and the United Kingdom. Empirical evidence from these countries is presented to demonstrate that this program can be delivered successfully and repeatedly, achieves consistent improvements in feed conversion efficiency (FCE) and margin along with major improvements in animal health, and produces external benefits in the form of decreased GHG emissions.

**SCOPE FOR IMPROVING DAIRY COW NUTRITION AND MANAGEMENT**

A general and useful definition of efficiency in dairy production is the conversion of feed nutrients to milk solids. Some farms are at the leading edge of efficiency with little scope for further improvement, whereas many are operating well below the upper limits of economically justified technical efficiency. Colman and Zhuang (2006) estimated that during 2002 to 2003, only 60% of milk in England and Wales was produced at a total cost below the average milk price, with only 40% of producers operating with a positive net margin. Comparable levels of economic inefficiency exist elsewhere, including the United States, and have contributed to the rapid exodus of producers, large and small, seen in many dairy economies over the last decade (USDA, 2007).

Total feed costs (including home-grown forages and feeds plus purchased feeds) typically account for more than 60% of average variable costs per unit of milk produced in most markets. Consequently, more efficient nutritional management has the potential to raise overall productivity and herd profits. For example, in the United States, cost of production budgets showed that feed costs on average were 78% of operating costs and 49% of total costs (ERS, 2010). This situation leads to the central argument of this paper, that increasing FCE is a key to improving herd profitability. A secondary output is that increased FCE will result in significant decreases in the amounts of GHG and manure (including N and P excretion) associated with production of each liter of milk. Such improvements should be welcomed by all countries that intend to remain in dairy production by being progressive, competitive, and consumer friendly.

In this paper, FCE is defined as kilograms of energy-corrected milk (ECM) produced per kilogram of feed DMI, with ECM containing 4.0% fat and 3.3% total protein (Tyrrell and Reid, 1965). In some countries, lower milk solids contents are used to standardize ECM, with the United States often using 3.5% fat and 3.1% true protein. Given that FCE is an approximation of overall nutrient use, particularly dietary energy, it is imperative that ECM be used rather than observed milk volume or weight without regard for its composition so that comparisons of FCE can be made within the farm and among farms.

Feeding systems used worldwide assume certain digestibilities and efficiencies of nutrient use in calculating requirements for energy and also make estimations of voluntary DMI for cows allowed to consume TMR. For example, the NRC (2001) system predicts that a cow in mid-lactation, at zero energy balance, and producing 40.0 kg of milk containing 4.0% fat and 3.1% true protein (i.e., ECM of 40.0 kg/d), will consume 26.9 kg of DM. Thus, the assumed FCE in the NRC system (NRC, 2001) for such cows, neither gaining nor losing body condition, is approximately 1.49 (i.e., 40.0 kg of ECM/26.9 kg of DMI). Under many conditions in the field, cows fail to produce the expected quantity of ECM from a given DMI and consequently FCE decreases. A
Lactating Cows

The rumen is the main site of digestion for ingested feed in ruminant animals, and maintenance of an active anaerobic microbial population ensures extensive fermentation of plant NDF. Other plant carbohydrates including sugars, starches, and pectins also are fermented to varying extents. Energy released from such processes, along with extensive degradation of dietary CP, is used to support growth of the resident microbial biomass. The main end products of carbohydrate fermentation are VFA, which are absorbed from the rumen and serve as the principal source of nutrients for the animal’s maintenance and productive demands. Collectively these processes, as reviewed by Beever (1993), affect total feed intake and level of milk production. The small intestine is the principal site of digestion of microbial protein and undigested feed protein (Beever and Siddons, 1986), plant and microbial lipid, and any unfermented feed starch.

Methane is an end product of rumen digestion, produced from carbon dioxide and hydrogen gas released during carbohydrate fermentation. The production of methane has a critical role in maintaining the oxidation-reduction state of the rumen environment and can account for between 2 and 12% of total digestible energy intake (Johnson and Johnson, 1995). Sutton et al. (1991) reported daily methane outputs between 0.36 and 0.54 kg for lactating dairy cows, depending on dietary feed intake and composition. Numerous studies have examined key dietary factors affecting methane production in ruminants (Blaxter and Clapperton, 1965; Moe and Tyrrell, 1979; Beauchemin et al., 2008b). Reynolds et al. (2011) reported that DMI was the dominant determinant of methane output. When DE (as a measure of fermentable OM) was included in their regression analysis, only a marginal improvement was noted in this relationship. Methane production is affected by the amount of digestible fiber in the ration, with Blaxter and Clapperton (1965) and Mills et al. (2001) demonstrating decreased methane output relative to feed DMI as the amount of cereal concentrates relative to forage was increased in the diet, although the relationships were curvilinear and decreases were less pronounced as starch inclusion increased.

Fiber-degrading bacteria are most efficient at a rumen pH above 6.0 (Mould et al., 1983). With increasing acidity, their functionality and growth rates are impaired, which can allow less desirable bacteria to dominate, as seen when high-starch feeds are provided in discrete meals (Krause and Oetzel, 2005). This situation inevitably leads to increased lactic acid production, causing rumen pH to fall further. Such conditions can be difficult to reverse and if they persist may lead to subclinical or clinical lactic acidosis (Bramley et al., 2008).

Optimization of rumen function requires the provision of rations suitably balanced for chemical nutrients, specifically the relative amounts of carbohydrate and protein considered to be potentially degradable by the rumen microorganisms. Equally there are other requirements for optimal fermentation, including maintenance of an average daily pH above 6.0 and minimal diurnal pH variation. The rumen contents must be continuously mixed to increase the intimacy between ingested feed particles and the microbial population. Active bouts of rumination aid the process of feed breakdown, thus increasing the overall rate and extent of digestion in the rumen. Extensive rumination promotes saliva secretion, with significant amounts of bicarbonate and phosphate buffers being produced that in turn support improved rumen pH conditions. Both rumen mixing contractions and rumination require suitable tactile stimulation of the rumen wall, which must be provided through the provision of longer forage particles, commonly referred to as physically effective fiber.

Against these factors, the advent of more highly digestible grasses and legumes and the harvest of these at less advanced stages of maturity to achieve higher nutritive values have resulted in many forages containing relatively low amounts of physically effective fiber. In addition, forages such as corn silage are chopped much shorter before ensiling to aid compaction in the silo and minimize in-silo waste. It follows, therefore, that many rations being fed to dairy cattle may lack the appropriate amount of physically effective fiber to promote optimal rumen mixing and rumination.

Under such conditions, both rate and extent of fiber digestion may be decreased (Beauchemin, 2007), which affects total DMI, feed digestion, and overall nutrient supply. Although contents of ME or NE of forages and other feeds can be estimated by laboratory analysis, this potential energy content will not be realized by the cow during the processes of digestion if rumen conditions are suboptimal. Using assumptions in current feeding standards (e.g., NRC, 2001), a modest 6% impairment in overall digestion due to compromised rumen function is sufficient to cause a 10% decrease in milk and milk solids yields.

Supplying rations with adequate amounts of physically effective fiber to optimize rumen function and feed utilization, however, is not as straightforward as it may appear. Providing long forage such as mature hay or cereal straw for free-choice consumption does not guarantee that it will be consumed when more desirable feeds are offered. Moreover, the physical characteristics of suitable physically effective fiber have not been adequately defined (Yang and Beauchemin, 2006). Although use of the Penn State forage particle separator has been an important management tool (Kononoff et al., 2003), it is only able
to differentiate particles by length and fails to recognize other physical attributes that may be of equal or greater importance. The KMF system attempts to address both the amount and characteristics of physically effective fiber. As discussed later, the KMF system focuses on full incorporation of physically effective fiber into well-mixed TMR to decrease the animal’s ability to sort the ingredients. The system also recognizes some of the other important characteristics of physically effective fiber necessary to optimize rumen function.

It follows that the concept of FCE is a critical measure of dairy cattle productivity, as discussed by Beever and Doyle (2007). Swine and poultry producers have successfully identified, measured, and attempted to increase FCE (usually measured as weight gain divided by as-fed feed intake) to improve business viability, with higher product outputs per unit of feed leading to lower feed costs per unit animal product and improved margins. Better nutrition and improved genetics have contributed to such effects, with some of these gains achieved by decreasing carcass fat content, which is recognized to be energetically more expensive to produce than lean tissue with its corresponding greater water content (Sandberg et al., 2005). Beef producers also realize the importance of FCE, but dairy producers have been slow to embrace the concept. Average FCE on many dairy farms is between 1.15 and 1.25 kg of ECM per kilogram of DMI, yet values of 1.50 to 1.60 kg/kg are achievable (NRC, 2001). Indeed, some herds achieve FCE >1.70 kg/kg and theoretically could reach close to 1.80 kg/kg (when discounting body condition loss), but only by increasing DMI or diet digestibility (VandeHaar, 1998). As developed later, a modest increase in FCE of 0.2 kg/kg has the potential to increase annual milk yields by more than 900 kg per cow (>3.2 kg/d extra milk), with no increased feed use. One major reason for low herd FCE is poor nutrition and feeding practice. Avoiding rumen and cow health issues, and as a consequence decreased FCE, involves careful nutritional and feed management.

The achievement of high FCE requires optimal rumen conditions and provision of adequate physically effective fiber. The source, maturity, and processing of structural fiber sources have been the subject of much research for their combined effects on rumen function. The physical form of the same fiber source can greatly affect rumen function and cow performance. Feeding small amounts of cereal straw (minimum 0.5 kg/d for milking cows) as a source of structural fiber has been proposed, and encouraging results have been reported with straw of suitable length (4 to 8 cm) and structure incorporated into mixed rations (Beauchemin et al., 2008a). In contrast, providing ryegrass straw either as a pellet (ground) or cube (coarse chopped) to cows grazing irrigated pasture showed no positive effects on milk production, milk composition, rumen pH, or time spent ruminating per unit of DMI (Wales et al., 2001). These results suggest method of straw inclusion in the ration is important, and the desired effects of improved rumination, optimized retention time, and more complete ruminal digestion are unlikely to be achieved by simply providing free access to straw or by grinding or pelleting. Inclusion of properly processed straw along with the other forages and feeds in a well-mixed TMR minimizes sorting and ensures proper consumption of the desired diet, whether in confined feeding situations or with cattle grazing pasture and fed a supplemental grazing mixed ration.

Changes to other aspects of nutritional management also can bring sizeable gains in FCE. The CP content of early season grass may be as much as 25 to 30% in excess of the cow’s requirements (NRC, 2001). This presents a conundrum for scientists and nutritionists; pasture plants require abundant N fertilizer to optimize plant photosynthesis and pasture growth, but overfeeding CP represents a loss of dietary CP and energy for the cow and increases the environmental effect of dairy production. Furthermore, feeding excessive amounts of protein in early lactation may accelerate BCS loss as cows respond to produce more milk (Whitelaw et al., 1986). In turn, excessive BCS loss can negatively affect fertility (Pryce et al., 2004) and is suggested as one reason why a significant number of pasture-based herds experience extended calving periods and relatively low conception rates despite modest levels of milk production (Mee, 2004). Strategic use of grazing mixed rations that aim to provide additional quantities as well as more balanced nutrients and avoid overfeeding protein can deliver major financial benefits.

**Dry Cows**

Preparation of the cow before calving will affect subsequent lactation performance and achieved FCE. Calving represents the single biggest insult for any cow during her annual cycle of milk production, yet the high incidence of health problems at and after calving noted on many farms represents an enormous burden on profits and on animal welfare. A survey of over 600,000 cows removed from almost 6,000 herds (through culling or death) over a 5-yr period showed an estimated 25% left during the first 60 d after calving (Fetrow et al., 2006). Clearly most of these were involuntary culls or deaths of cows that had not remained in the herd long enough after calving to achieve their milk income potential but had all the accrued costs of breeding, gestation feeding and management, and calving.

Many dry cow feeding strategies have been based on the perception that additional nutrients supplied before calving will promote higher peak milk yields and avoid the consequences of compromised feed intakes after calving. These ideas are well-embedded in the history of dairy production (Boutflour, 1928; Grummer, 1995), but recently the practice of extra feeding during the last weeks of the dry period has been challenged (Drackley and Dann, 2008). Surprisingly little nutritional evidence is...
available to suggest that cows require ad libitum intake of higher energy diets during the precalving dry period. To the contrary, excessive energy intake, even in cows of low to average BCS, has been shown to predispose cows to health problems around calving and the early postcalving period, including dystocia, fatty liver, and ketosis (Dann et al., 2006; Douglas et al., 2006; Janovick and Drackley, 2010).

The principal reason for adoption of higher-intensity feeding before calving has been the notion that appetites naturally decline toward calving and that dry cows need to be fed higher energy density diets to compensate for lower DMI (Grummer, 1995). Recent studies, however, have shown that the extent of the decline in prepartum DMI is related to the energy density of the diet (Grummer et al., 2004; Richards et al., 2009; Janovick and Drackley, 2010). Beever (2006) and Drackley and Dann (2008) proposed an alternative feeding strategy to control DMI and nutrient intake during the dry period to ensure that all nutrient requirements are met while maintaining more satisfactory DMI through to calving. This new approach relies on feeding TMR containing high amounts of bulky roughages such as cereal straw (ca. 30 to 50% of total DM). These high-fiber rations can be readily prepared and delivered by the KMF system (Richards et al., 2009), unlike most other feeding systems. The system has brought substantial gains in the field, with fewer difficult calvings and decreased periparturient health issues (Beever, 2006).

A SYSTEM FOR DELIVERING IMPROVED DAIRY COW NUTRITION

The KMF dairy system is the outcome of on-farm experience and supporting research evidence. The system offers a series of unique solutions based on nutritional principles, as outlined previously, and aims to optimize rumen function and productivity while decreasing production-related disorders in dairy cattle. Central to the system is the consistent delivery of properly mixed TMR and grazing mixed rations, consisting primarily of conserved forages together with energy- and protein-rich supplements, of suitable nutritional composition to meet the nutritional requirements of the animal. Long forages, such as cereal straw, are included in the ration, which after suitable processing within the mixer wagon provide the requisite amounts of physically effective fiber of unique specification (i.e., Mech-fiber) to promote rumen function. Extensive use of home-grown, high-quality silages and pasture (as appropriate) is recommended.

Several major components have been identified that farmers can implement using the KMF mixer wagon (Richard Keenan & Co.), supported by the company’s nutritionists. Of central importance are the unique design characteristics of the KMF mixer wagon, in terms of functionality and operation, with slowly revolving paddles and a series of fixed knives in the mixing chamber providing a gentle chopping and mixing action, ensuring correct ration mixing and inclusion of optimal amounts of Mech-fiber. This contrasts with many other TMR mixers, including vertical mixers employing a central rotor with attached knives, where the more aggressive action can result in unevenness and over-processing of long forages (Buckmaster, 2010). Loading order of feeds, load size relative to machine capacity, tractor speed, and mixing time are all controlled closely as key determinants of the physical characteristics of the final mixed ration.

This need to standardize mixing procedures led to development of Performance Acceleration and Control Enhancement (PACE; Richard Keenan & Co.), a computer-controlled feeding system fitted to the mixer wagon. The computer algorithms embedded within the system aim to optimize ration processing and mixing protocols to provide consistent TMR containing optimal amounts of Mech-fiber, specifically defined in terms of length, specific gravity, compressibility, and water-holding characteristics. The algorithms were based on critical analysis of the performance data from more than 9,000 dairy herds representing 1 million lactating dairy cows worldwide, and are constantly updated.

The development of PACE allowed knowledge on ration preparation and feeding to be suitably collated into an Internet-supported system that is available to farms globally. To operate the system, the customer categorizes available feed ingredients and formulates a chemically balanced ration. Using PACE, each ration is then optimized with respect to loading and mixing procedures via a dedicated Internet service. Subsequently, the mixer operator follows the specific details for each ration by means of the weigh-scale readout fitted to the mixer wagon for the production of consistent rations for all classes of livestock on the farm. At the same time, information on actual loading and mixing processes is recorded and fed back to a central database for publication on the customer website.

Analysis of these data allows the customer and nutritionist to determine degree of compliance in the mixing process and to make adjustments if required. With PACE, underloading of any specific ingredient cannot occur because the next ingredient will not be declared on the weigh-box until the correct amount of the current feed ingredient being loaded has been added. In the same way, materials requiring processing time, including cereal straw, cannot be underprocessed because the next ingredient will not be displayed until the appropriate number of mixing revolutions has been completed. Overloading and overprocessing cannot be rectified at the time of loading and mixing, but these can be dealt with subsequently when information relating to achieved loading and processing procedures is downloaded to the farm’s computer for scrutiny of ration preparation compliance.

The perception that ration structure is unaffected by machine type or its
operation is widespread among farmers and their advisors (Buckmaster, 2010). In a recent study (Humphries et al., 2010), cows fed a TMR prepared with a KMF mixer produced more milk (40.3 vs. 39.3 L/d) and additional milk protein compared with the same cows fed the same feed ingredients in a TMR prepared using a vertical auger mixer. Continuous measurement of rumen pH showed that KMF-fed cows spent 28% less time below pH 6.0 (5.28 vs. 7.29 h/d), whereas differences in the proportion of long particles and mean particle size (both larger for the vertical mixer than for KMF) decreased intake rate and increased total time spent eating when cows were fed from the vertical mixer. The researchers concluded that the KMF ration had beneficial physical characteristics that promoted more optimal rumen fermentation, in turn contributing to the higher production of milk and milk protein.

The system places importance on both heifer rearing and dry cow management and recommends high inclusion rates of cereal straws in the final TMR for both classes of livestock. For growing heifers, more consistent intakes of TMR of lower nutrient density significantly decreases variation in their growth and development as well as age at first calving and prevents them from becoming overconditioned before calving (Hoffman, 2007). With dry cows, feeding a controlled-energy, high-fiber (CEHF) TMR, of low energy density with high amounts of Mech-fiber due to high cereal straw inclusion (ca. 30 to 50% of total DM), has been shown to bring large benefits by decreasing health disorders around calving, as discussed later. In this respect, the KMF mixer together with PACE will achieve full incorporation of large amounts of cereal straw in TMR that will be readily consumed by dry cows without significant sorting (Richards et al., 2009).

A further element of the system relates to nutritional management of the milking cow. In-parlor feeding of additional concentrates is discouraged because of known negative effects of large discrete meals of concentrates on rumen function. Instead, housed cows are fed a single TMR irrespective of DIM or milk yield, with grouping of cows according to lactation stage no longer being necessary. This simplifies herd management, and significant improvements in postpeak persistency have been noted using this approach (D. E. Beever, unpublished observations).

For pasture-fed cows, optimizing the utilization of grown grass is paramount and requires excellent pasture-management skills. Optimal utilization of consumed grass by the cow is equally important, and feeding balanced grazing mixed rations, ideally immediately before milking, and discontinuing the practice of in-parlor feeding can bring significant benefits (Beever and Doyle, 2007). This practice allows possible pasture supply shortfalls to be overcome, as well as any grass compositional inadequacies, particularly in respect to structural fiber levels as often seen in spring grass. Well-formulated grazing mixed rations will complement rather than replace grazed pasture, with associated gains in milk yield and overall margins without markedly increasing total feed costs per unit of milk produced (Beever and Doyle, 2007).

The final element of the system is measurement of animal performance. Previously this was accomplished by manual capture of data such as cow number, average DIM, milk yield and composition, ration composition, amount fed, and feed costs. This has now been replaced by automatic data capture using PACE, allowing the total amount of feed offered to be compared with milk yield and composition data (which can be readily uploaded) for regular determination of FCE, daily margins, and total feed costs per unit of milk produced. These measures are more relevant than margin over purchased feed, which does not accurately reflect total feed usage and cost. Annual herd measurements of FCE allow gross performance and progress to be determined, and shorter-term measures are a valuable diagnostic for timely interventions as necessary. User data obtained as described above form the basis for the following evaluation of the economic effects of the proposed system.

EMPIRICAL ANALYSIS OF THE EFFECTS OF APPLYING THE KMF SYSTEM

The objective of the nutritional advice offered to dairy farmers who adopt the system is to assist in the achievement of targeted gains in nutritional efficiency and herd health status. These farmers are asked to submit detailed statistics that enable changes in FCE and margin to be measured. Not all farmers accept this nutritional advice; either they make their own independent decisions or employ other advisors. However, evidence of consistent significant improvements in FCE, margin, and animal health achieved by adoption of significant elements of the system has been obtained in both France and the United Kingdom. A brief consideration of the implications of such improvements on methane emissions is also provided.

Effects on FCE and Margins per Cow

The logic of the economics behind improvements in margin from increased FCE is simple. If DMI per cow averages 20.5 kg/day, an FCE of 1.2 kg/kg delivers 24.6 kg of ECM. If improved ration management can raise FCE to 1.3 kg/kg, the average daily yield of ECM at the same DMI will increase to 26.7 kg. The value of any margin gain will depend on the extent to which FCE has been improved by increasing milk output or by decreasing feed inputs, as well as by prevailing milk price and feed costs. Taking the above simple example, a 0.1 gain in FCE delivering an extra 2.1 kg of milk/d would be worth $0.73/d per cow on the gross and net margins at a milk price of $0.35/kg, assuming that the nutritional advice did not entail additional costs. Given that the farms of the herds studied had already invested in a TMR mixer
wagon, no additional machinery or labor costs to adopt the proposed nutritional program were assumed. Furthermore, as the system aims to maximize the use of home-grown feeds, it is likely that cost per unit of total feed DM could be decreased.

As can be seen from the data presented below, a significant number of farms that adopt the system actually see decreased DMI despite rising yields and FCE. Table 1 indicates the average FCE improvements in the 4 yr from 2006 to 2009 for French and United Kingdom herds receiving nutritional advice after buying a Keenan mixer wagon. The results have been converted from European measures to those applicable in the United States, with an assumed milk price of $0.35/kg of ECM and feed cost of $0.22/kg of DM. From this data set of 1,086 farms, improvements in FCE were strongly associated with increases in margin over all feed costs in both France and the United Kingdom (Figure 1). This relationship demonstrates that FCE is a major driver of margins for dairy farms, and increases in FCE should lead to increases in margin.

Formally the relationship between FCE and the margin over total feed costs (M) is defined as

\[ M = PY - CD, \]  

where \( P = \text{price (cents/kg) of ECM}; \) \( Y = \text{yield of ECM (kg/d) per cow}; \) \( C = \text{unit cost (cents/kg) of the diet formulation on a DM basis}; \) \( D = \text{DMI (kg/d)}; \) and

\[ \text{FCE} = \frac{Y}{D}. \]  

Dividing equation 1 through by \( Y \) then gives

\[ M_u = \frac{P - [(CD)/Y]}{Y} = P - \frac{C}{\text{FCE}}, \]  

where \( M_u = M/Y, \) the unit margin over feed costs per unit of production (kg of ECM).

Both this unit margin \( (M_u) \) and, in turn, the unit feed costs are critical factors for dairy producers not only in terms of enterprise profitability but also for economic competitiveness and risk-bearing ability. Equation 3 illustrates the direct relationship between FCE and margin; as FCE increases, so margin increases monotonically. This relationship holds even when unit ration costs increase as a function of increasing FCE as may be the case with higher performing herds, provided the marginal increase in feed cost per unit of FCE change is less than the average cost per unit of FCE change.

Because both or either of the numerator \( \text{(ECM)} \) and denominator \( \text{(DMI)} \) in equation 2 may change, however, the actual margin improvement of a given unit of FCE change will vary because of the different prices per kilogram of milk and feed experienced by producers. For example, in the United Kingdom data from 2006 to 2009, only 34% of the herds had both increased output and decreased input. However, 72% showed an increase in FCE, and approximately 80% showed a margin increase at constant prices. The cohort of producers changed each year, but responses to the nutritional advice were consistent between years (Table 1).

French producers had little opportunity to increase annual milk sales because of milk quota restrictions and therefore strove to improve annual margins through increasing FCE with higher milk yields and decreased DMI and then decreasing cow numbers. In all 4 yr the French samples had average FCE increases in excess of 0.15 kg of ECM/kg of DMI, which is substantial from an average base FCE of 1.2 kg/kg. The difference between the starting position and 12 mo later was significantly \((P < 0.001)\) greater than zero when applying a one-tailed \( t \)-test. This improvement was achieved by increasing average milk yield by 2.2 kg/d per cow and at the same time decreasing DMI by between 0.96 and 1.11 kg/d per cow depending on the year. Both components of improvement also were significant \((P < 0.001)\)

### Table 1. Annual responses of French and UK dairy farm cohorts to Keenan Mech-fiber system and nutritional advice, 2006 to 2009

<table>
<thead>
<tr>
<th>Variable†</th>
<th>France</th>
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<th>UK</th>
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<tr>
<td></td>
<td>2006</td>
<td>2007</td>
<td>2008</td>
<td>2009</td>
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<td>Number of herds</td>
<td>151</td>
<td>148</td>
<td>171</td>
<td>205</td>
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<td>FCE increase, kg of ECM/kg of DMI</td>
<td>0.18***</td>
<td>0.18***</td>
<td>0.15***</td>
<td>0.16***</td>
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<td>Change in mean ECM yield, L/d</td>
<td>2.53***</td>
<td>2.51***</td>
<td>1.66***</td>
<td>2.08***</td>
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<td>Change in DMI, kg/d</td>
<td>-1.05***</td>
<td>-0.96***</td>
<td>-1.11***</td>
<td>-1.09***</td>
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<td>Change in margin, $/d</td>
<td>1.12***</td>
<td>1.09***</td>
<td>0.83***</td>
<td>0.97***</td>
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<tr>
<td>Change in margin per 0.1 change in FCE, $/d</td>
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<td>FCE increase, kg of ECM/kg of DMI</td>
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<td>0.08***</td>
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<td>Change in mean ECM yield, L/d</td>
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</tr>
<tr>
<td>Change in DMI, kg/d</td>
<td>-0.20</td>
<td>-0.37*</td>
<td>-0.19</td>
<td>-0.04</td>
</tr>
<tr>
<td>Change in margin, $/d</td>
<td>0.58***</td>
<td>0.44***</td>
<td>0.41***</td>
<td>0.61***</td>
</tr>
<tr>
<td>Change in margin per 0.1 change in FCE, $/d</td>
<td>0.66</td>
<td>0.54</td>
<td>0.56</td>
<td>0.67</td>
</tr>
</tbody>
</table>

†FCE = feed conversion efficiency; ECM = energy-corrected milk, adjusted to 4.0% fat and 3.3% CP.

‡Milk valued at $0.35/kg of ECM and feed at $0.22/kg of DM.

***Different from zero by one-tailed \( t \)-test, \( P < 0.001 \); *different from zero by one-tailed \( t \)-test, \( P < 0.05 \).
in all 4 yr. In the United Kingdom, where quota restrictions were less rigid, the pattern of response to the nutritional advice was different. The increase in FCE again was significant \((P < 0.001)\) for all 4 yr, varying between 0.07 and 0.09. Average ECM yield increases, of between 1.01 kg/d in 2007 (a year of exceptionally poor forage quality nationwide) and 1.78 kg/d in 2009, also were significant \((P < 0.001)\) in all years. A notable difference between countries, however, was the smaller and statistically nonsignificant decreases in DMI observed in the United Kingdom compared with France.

It is striking to observe how close the measured margin changes per 0.1 unit increase in FCE were to the theoretical argument set out earlier in this paper. For the United Kingdom, the increases averaged $0.61 per 0.1 unit FCE increase, compared with $0.59 in France, with the decreases in DMI accounting for around 25% of the improvement in margin. However, these averages hide considerable variation in performance within the 4 producer cohorts in each country, which is not entirely surprising given the range of specific factors that affect individual herd performances.

This variation is revealed in the FCE distributions shown in Figure 2, which presents the changes over 12 mo for the French and UK herds moving onto the KMF system in 2009. Here the overall improvement in FCE is illustrated by the rightward shift of the distribution, by the tightening of the distribution and decrease of the left-hand tail, and by the increase in modal frequency. At the same time Figure 2 illustrates the wide variance of FCE of herds coming onto the system, with a range from around 0.6 to 1.5 kg/kg. By the end of 1 yr, this range narrowed slightly to between 0.8 and 1.6 kg/kg but still indicated considerable opportunity for further improvement in many herds.

A further analysis demonstrates the synergies of the technology and the advantages of full compliance within the system. A comparison of 20 dairy farms in the USA and Europe, involving 3,399 cows averaging 190 DIM, is presented in Table 2. Changes in performance from the starting (pre-system) position to that at 40 and 80 d after adoption of all or parts of the system are tabulated. Average milk yield increased by 1.4 kg/d per cow (different than zero, \(P < 0.001\), by one-tailed t-test), which resulted in significant \((P < 0.001)\) improvements in total fat and protein yields despite no marked changes in milk composition. Overall ECM yield increased by 1.5 kg/d \((P < 0.001)\) with no change in total DMI, resulting in a modest improvement in FCE \((P < 0.01)\). Subsequently, data are presented for 10 farms considered to be progressive adopters of the system, who combined the Keenan mixer with PACE and varying amounts of the required nutritional management protocols, and for the remainder deemed to be only partial adopters, who used the Keenan

![Figure 1. Relationships between feed conversion efficiency (FCE) and adjusted margin (in US dollars) from farms that adopted the Keenan Mech-fiber system in France (top) and the UK (bottom) in 2006 to 2009. Color version available in the online PDF.](image-url)
mixer, PACE, and machine operations but did not implement the nutritional management protocols. The progressive adopters had a larger gain in milk yield (1.8 kg/d, \(P < 0.001\)) with a similar net gain in total fat and protein yields (\(P < 0.01\)). With an average decrease in DMI of 1.5 kg/d (\(P < 0.01\)), the yield increase of 1.8 kg of ECM/d (\(P < 0.001\)) equated to a net FCE gain of 0.18 kg of ECM/kg of DMI (\(P < 0.001\)). For those farms considered to be partial adopters, smaller gains in milk yield (\(P < 0.01\)) and ECM yield (\(P < 0.05\)) were noted, associated with increased DMI and a small nonsignificant decrease in FCE.

Based on average milk prices and feed costs prevailing in the United States at the time of the study, both milk income (\(P < 0.01\)) and margin (\(P < 0.001\)) were significantly increased for the progressive adopters compared with their average start position, with a net daily margin gain of $0.98/cow. In contrast, partial adopters showed a smaller gain in milk income (\(P < 0.05\)), but increased feed costs resulted in an average daily margin improvement of only $0.13/cow. This provides evidence of the importance of full system adoption to deliver better margins through improved FCE. Note also that such changes were obtained in a relatively short time period, with additional gains expected through continuation of the system.

Although it is important to understand average margin gains achieved with the system, it is also important to consider the maximum potential gain because this serves as a true measure of technical efficiency. This is presented in Table 3 for 10 top-performing herds (one Jersey, remainder Holstein) located in Denmark (3), France (1), Sweden (4), and the UK (2), representing 1,730 cows (average 184 DIM). All farms were considered to be complete adopters, operating the full system including PACE and nutritional protocols. The data were weighted according to herd size.

Milk yield averaged 34.1 kg/d, which with excellent milk solids content resulted in a combined fat plus protein yield of 2.5 kg/d. Yield of ECM averaged 34.7 kg/d at a DMI of 20.9 kg/d, resulting in a mean FCE of 1.66 kg/kg. These field data show that high and consistent FCE can be achieved at relatively modest DMI, confirming the importance of optimizing ration digestibility to be in concert with the formulated dietary specifications. Many farmers and their

### Table 2. Average performance of 20 herds classified as progressive adopters or partial adopters of the Keenan Mech-fiber (KMF) system compared with previous nutritional practices (start)

<table>
<thead>
<tr>
<th>Farm class</th>
<th>Milk, kg/d</th>
<th>Fat + protein, kg/d</th>
<th>ECM, kg/d</th>
<th>DMI, kg/d</th>
<th>FCE, kg/kg</th>
<th>Milk income, $/d</th>
<th>Feed costs, $/d</th>
<th>Margin, $/d</th>
<th>Gain for KMF, $/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>All farms (n = 20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start</td>
<td>28.1</td>
<td>2.05</td>
<td>28.1</td>
<td>21.9</td>
<td>1.28</td>
<td>9.82</td>
<td>4.82</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td>KMF</td>
<td>29.5***</td>
<td>2.17***</td>
<td>29.6***</td>
<td>21.9</td>
<td>1.35**</td>
<td>10.37***</td>
<td>4.82</td>
<td>5.55***</td>
<td>0.55</td>
</tr>
<tr>
<td>Progressive adopters (n = 10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start</td>
<td>27.1</td>
<td>1.97</td>
<td>27.0</td>
<td>22.6</td>
<td>1.19</td>
<td>9.45</td>
<td>4.98</td>
<td>4.47</td>
<td></td>
</tr>
<tr>
<td>KMF</td>
<td>28.9***</td>
<td>2.10**</td>
<td>28.8***</td>
<td>21.1**</td>
<td>1.37***</td>
<td>10.09**</td>
<td>4.64</td>
<td>5.45***</td>
<td>0.98</td>
</tr>
<tr>
<td>Partial adopters (n = 10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start</td>
<td>29.0</td>
<td>2.12</td>
<td>29.1</td>
<td>21.2</td>
<td>1.37</td>
<td>10.19</td>
<td>4.66</td>
<td>5.53</td>
<td></td>
</tr>
<tr>
<td>KMF</td>
<td>30.0**</td>
<td>2.23*</td>
<td>30.5*</td>
<td>22.7</td>
<td>1.34</td>
<td>10.66*</td>
<td>5.00</td>
<td>5.66</td>
<td>0.13</td>
</tr>
</tbody>
</table>

---

1 ECM = energy-corrected milk, adjusted to 4.0% fat and 3.3% protein; FCE = feed conversion efficiency.

2 Milk valued at $0.35/kg of ECM and feed at $0.22/kg of DM.

* \(P < 0.05\), ** \(P < 0.01\), *** \(P < 0.001\); different from zero by one-tailed t-test.
advisors believe that greater milk yields are only possible with greater DMI, even though diet digestibility is well known to decline as DMI increases (NRC, 2001). Furthermore, additional feed DMI increases costs with a possible negative effect on daily margin, despite any achieved increase in milk income.

**Effects on Animal Health**

A study of 277 farms involving 27,470 cows in France, Ireland, Sweden, and the UK during 2006 to 2007 examined the effect of the Keenan CEHF feeding strategy for dry cows on animal health issues. Average herd size ranged from 53 (France) to 189 (UK) cows, with average annual herd milk yields between 7,182 kg (Ireland) and 9,473 kg (Sweden). All herds were above national averages in size and annual yield, which is important to note because intensively managed herds are perceived to have increased health problems relative to the norm. Conditions of study enrollment included that the herds had adopted the CEHF feeding system for dry cows for a minimum of 6 mo and that suitable records were available for the incidence of metabolic disorders during respective periparturient periods before and after adoption of the new system. The health incident data were obtained from each country’s national recording service.

For the 5 monitored conditions shown in Table 4, adoption of the Keenan CEHF system resulted in a significant decrease in incidence rates. Retrospective data before system adoption showed a combined incidence rate (per 100 cows calved) of 15.6 assisted calvings, 9.9 milk fevers, 10.7 retained placentas, 6.6 ketosis, and 2.7 displaced abomasums. Collectively these amounted to 45.4 disorder cases per 100 cows, although some cows experienced more than one metabolic insult. Such a high figure is alarming as a measure of the size of the health problem in the global dairy industry and the likely downstream effects on the ensuing lactation, including the ability of the cows to rebreed.

Adoption of the CEHF feeding strategy decreased overall incidence of metabolic insults to 16.2 cases per 100 cows calved, most notably in occurrence of displaced abomasum (85.6% decrease), ketosis (78.7%), and milk fever (74.8%). France had the largest original incidence of assisted calvings and retained placenta, which are interrelated, with incidence rates falling by 60 and 45%, respectively, after system adoption. The UK had the greatest initial incidence of milk fever (16%), which was decreased by almost 80% after adoption of the CEHF system. The incidence of displaced abomasum in France and the UK (ca. 5 per 100 cows calved) was decreased to less than 1 case per 100 cows calved after adoption of the...
CEHF system. The real costs of such problems are difficult to estimate and document but include compromised milk production, decreased fertility, and increased culling. The savings made by adopting the CEHF feeding strategy are certainly large and call for further research.

**Environmental Effect of Improved FCE**

The production of milk has both direct and indirect environmental costs. As dairy industries worldwide strive to decrease GHG emissions, serious and continued consideration needs to be given to the implementation of emerging innovative technologies. Among indirect costs, forage harvesting, processing supplementary feeds, ration preparation and presentation, and the provision and suitable environmental control of facilities for housing cows and milk harvesting have all become increasingly sophisticated where mechanical operations have replaced labor in producing milk. This change does not, however, preclude seeking and acting upon opportunities to further decrease the environmental costs of producing milk, through, for example, improved equipment maintenance, the use of lower-horsepower tractors where possible, and other energy-saving approaches.

It is in the direct environmental costs of dairying, however, where the greatest gains are now likely to be achieved. Carbon and N emissions from cows are well documented, and the dairy industry is faced with making sizeable and sustained decreases without compromising annual milk outputs. Collective losses of carbon in feces, urine, and expired air (as carbon dioxide and methane) account for approximately 70% of total feed carbon, with N losses in feces and urine of a similar magnitude (Castillo et al., 2001). According to data from indirect calorimetry determinations of methane production by dairy cows (Kebrea et al., 2003), methane output for a cow consuming a typical dairy ration and producing 10,000 kg of ECM at a modest FCE of 1.3 was estimated to be >170 kg/yr. With no imposed ration ingredient changes and at the same milk yield, improving FCE to 1.5 by adoption of the KMF system was estimated to decrease annual output of methane by 22.7 kg, through a decrease in total feed DM required. This could result in an estimated methane burden of 1.53 kg/100 kg of milk compared with 1.76 kg/100 kg for cows at the lower FCE. Further increases in FCE to levels noted in some of the best herds would decrease this to below 1.40 kg/100 kg of milk, a net overall decrease of methane of more than 20%. The full effect of improving FCE on methane emissions per kilogram of milk is presented in Figure 3, which shows a progressive decline from 2.26 kg of methane/100 kg of milk at an FCE of 1.0 kg/kg to 1.33 kg of methane/100 kg at an FCE of 1.7 kg/kg. This relationship indicates that decreases of between 0.09 and 0.20 kg of methane/100 kg of milk are possible for each 0.1 increment in FCE. Further gains would be achieved when systems of managing and feeding replacement calves and heifers are optimized.

The KMF system provides a unique example of an integrated technology that delivers measurable environmental gains while improving overall margins to dairy producers. This decrease in methane emissions has the potential to further increase the competitiveness of the system. If the United States pursues a regulatory policy toward GHG similar to those in Europe, users of the system should face a decreased regulatory burden. If a cap-and-trade policy were to be adopted, a potential income stream for users of the system through trading of carbon off-sets could be identified.

**SUMMARY: BENEFITS OF AN INTEGRATED SYSTEM TO IMPROVE FCE**

A significant number of dairy farmers could raise operational profitability by adopting the integrated nutritional practices embodied in the KMF system. The lactation data presented here show that, on average, producers in France and the United Kingdom increased FCE significantly in the first year following system adoption, for each of the years between 2006 and 2009. In France, an average FCE increase in excess of 0.15 kg of ECM/kg of DMI was noted. In the United Kingdom the pattern of response to the nutritional advice was similar but muted compared with the French data. The differential responses to degree of implementation confirm that the system is an integrated feeding approach and only through complete adoption can the maximum possible benefits be gained. Data from the best herds demonstrate the upper range of potential being achieved and could form a useful target for those farms operating with good genetics, good facilities, and high-quality forages and feeds but failing to deliver to their full potential.

The full economic gains from adopting the system exceed those of simply reformulating the lactating cow ration and improving FCE. Adoption of the CEHF dry cow ration decreases peripartal health problems, with associated economic benefits of decreased veterinary costs, decreased involuntary culling, and improved fertility. Many herds continue to experience significant health and fertility problems, and the improvements possible through adoption of the nutritional strategies of the KMF system are striking.

Dairy farms will be under continuing pressure to increase productivity and improve economic sustainability. At the same time, societal pressures will demand that these gains be achieved while decreasing the GHG burden of dairy production. By improving FCE, methane emissions per unit of milk produced are inevitably decreased as more feed carbon is retained in milk solids with increased productivity, which dilutes the production of methane associated with cow maintenance. The KMF system shows promise in meeting the seemingly opposing goals of increased productivity and decreased GHG emissions per unit of milk marketed.
Similar conclusions can be drawn with respect to the efficiency of N and P use for milk production. In our analysis, FCE emerged as a critical and far-reaching measurement of dairy farming efficiency. Increasing FCE is an indicator of improved performance in several important dimensions simultaneously, including producer profitability, animal health, and GHG emissions. It follows that use of FCE is a valuable benchmark indicator for different production systems. The United Kingdom data set for 2006 showed an average FCE of 1.27 kg of ECM/kg of DMI, with only 5% of producers achieving an FCE more than 1.50 at the beginning of the year. After 1 yr, 21% of farms met that standard, with the highest herd FCE at 1.68. In France only 6% of herds started the 2006 year with an FCE above 1.50, but after 1 yr, 36% of farms had achieved or exceeded this value. These field data confirm that substantial improvements in FCE are possible in a short time frame for dairy herds that adopt the KMF nutrition system.

**IMPLICATIONS**

Most dairy herds in the European Union currently are operating with an FCE of less than 1.20 kg of ECM/kg of DMI. Recent measures on typical dairy farms in the United States (D. E. Beever, unpublished data, 2011) indicated only a marginally better position, with most below an FCE of 1.30 kg of ECM/kg of DMI. Dairy producers at most levels of productivity could make significant improvements in profitability by adopting the KMF system, which is based on principles of nutritional science that are consistent with efficient feeding of healthy cows. An important aspect of this system is the CEHF ration strategy for preparing dry cows for calving, with substantial beneficial effects on cow health reported here.

With the prospect of more international competition among milk and dairy product markets and the growing pressures for decreased GHG emissions and other environmental contamination from dairy production, it is critical that all dairy sectors strive to improve technical and economic efficiencies. The Keenan Mech-fiber system represents an integrated technology that has been shown to improve FCE, animal health, and the environmental effect of dairy production. Use of such technology to improve dairy cow nutrition could be a critical step for many producers if they are to achieve sustainable economic efficiency and move closer to those producers already operating at the highest levels. Such technology has been shown to be useful regardless of production system.

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**LITERATURE CITED**


