Published December 5, 2014

The environmental impact of dairy production: 1944 compared with 2007[1]

J. L. Capper,* R. A. Cady,† and D. E. Bauman*[2]

*Department of Animal Science, Cornell University, Ithaca, NY 14853; and †Elanco Animal Health, Greenfield, IN 46140

ABSTRACT: A common perception is that pasture-based, low-input dairy systems characteristic of the 1940s were more conducive to environmental stewardship than modern milk production systems. The objective of this study was to compare the environmental impact of modern (2007) US dairy production with historical production practices as exemplified by the US dairy system in 1944. A deterministic model based on the metabolism and nutrient requirements of the dairy herd was used to estimate resource inputs and waste outputs per billion kg of milk. Both the modern and historical production systems were modeled using characteristic management practices, herd population dynamics, and production data from US dairy farms. Modern dairy practices require considerably fewer resources than dairying in 1944 with 21% of animals, 23% of feedstuffs, 35% of the water, and only 10% of the land required to produce the same 1 billion kg of milk. Waste outputs were similarly reduced, with modern dairy systems producing 24% of the manure, 43% of CH_4, and 56% of N_2O per billion kg of milk compared with equivalent milk from historical dairying. The carbon footprint per billion kilograms of milk produced in 2007 was 37% of equivalent milk production in 1944. To fulfill the increasing requirements of the US population for dairy products, it is essential to adopt management practices and technologies that improve productive efficiency, allowing milk production to be increased while reducing resource use and mitigating environmental impact.

Key words: carbon footprint, dairy, dilution of maintenance, environmental impact, greenhouse gas, productive efficiency

©2009 American Society of Animal Science. All rights reserved.

J. Anim. Sci. 2009. 87:2160–2167
doi:10.2527/jas.2009-1781

INTRODUCTION

Environmental considerations are receiving increasing priority upon political, social, and economic agendas, especially when related to agriculture. All food production has an environmental impact, and as the US and global populations continue to increase, it is critical to produce sufficient high-quality food from a finite resource supply while minimizing effects upon the environment. Agricultural practices have changed considerably over the past century: dairy production in the 1930–40s was characterized by pasture-based, low-input systems with correspondingly low milk production, providing a sharp contrast to modern high-input:high-output systems (Meigs, 1939; VandeHaar and St-Pierre, 2006). To achieve an economically and environmentally sustainable food supply, agriculturalists need to identify systems and practices that make the best use of available resources and minimize the potential environmental impact (Capper et al., 2008). However, a common perception is that historical methods of food production were inherently more environmentally friendly than modern agricultural practices. This is often reinforced by media portrayal of rustic pastoral scenes as the "good old days" compared with the perception of "factory farming" of today. We used a deterministic model (Capper et al., 2008) based on NRC (2001) nutrient requirements to evaluate the environmental impact of historical US milk production as exemplified by the US dairy system in 1944, compared with modern (2007) practices.

MATERIALS AND METHODS

This study utilized existing databases and required no Animal Care and Use Committee approval.

Dairy systems were modeled according to characteristic production practices of US dairy farms for the 2

[1]This work was supported in part by funding provided to Dale E. Bauman as Liberty Hyde Bailey Professor in the College of Agriculture and Life Sciences at Cornell University and by the Cornell Agricultural Experiment Station.

[2]Corresponding author: deb6@cornell.edu

Received January 9, 2009.
Accepted March 1, 2009.

Table 1. Characteristics of the 1944 and 2007 dairy production systems[1]

Variable	1944	2007
Breed	54% Jersey/Guernsey/Ayrshire (small) 46% Holstein/Brown Swiss (large)	90% Holstein
Milk yield per cow, kg/yr	2,074	9,193
Milk fat content, %	4.20 (small breed) 3.60 (large breed)	3.69
Milk protein content, %	3.50 (small breed) 3.20 (large breed)	3.05
Heifer:cow ratio	0.89	0.83
Heifer growth rate, kg/d	0.42 (small breed) 0.59 (large breed)	0.68
Age at first calving, mo	27.0	25.5
Breeding method	100% natural service	70% AI, 30% natural service
Bull:cow ratio	1:25	1:83
Principal forage sources	Pasture, hay	Corn silage, alfalfa silage
Diet type	Forage + concentrate	Total mixed rations

[1]Further details of 1944 system characteristics are given in the Materials and Methods section; details of 2007 system inputs and characteristics are presented in Capper et al. (2008).

time points according to published production data, with system inputs, population dynamics, and procedures as described previously in Capper et al. (2008), save for the amendments listed below. The system characteristics for each year are summarized in Table 1.

2007 Dairy Population Characteristics

The 2007 dairy system was modeled according to characteristic production practices of US dairy farms (USDA, 2007) with the total environmental impact based on national milk production and animal numbers (http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats). The 2007 annual milk yield averaged 9,193 kg per cow, which is equivalent to 29.3 kg/d when adjusted for a 14-mo calving interval (426 d) and a 60-d dry period (USDA, 2007). Milk fat (3.69%) and true protein (3.05%) concentrations represented US averages for 2007 (USDA/AMS, 2007). The current US dairy herd is predominantly Holstein, with AI accounting for 70% of successful conceptions (De Vries et al., 2008); therefore, sufficient bulls were included in the population to represent 30% of conceptions at a bull:cow ratio of 1:25 (Overton, 2005). No published nutrient requirements are specific to mature dairy bulls; therefore, rations for bulls were based on National Research Council (NRC, 2001) recommendations for nonpregnant, nonlactating cows at 45 mo of age and 825 kg of BW. Replacement adolescent bulls were included in the population at a ratio of 0.83 replacements for each adult bull, and rations formulated according to the nutrient requirements for 352 kg, the median BW for adolescent bulls with a growth rate of 880 g/d (NRC, 2001). Corn silage, alfalfa hay, dry ground corn grain, and soybean meal were identified by Mowrey and Spain (1999) as the major feedstuffs used in dairy production and were thus used to formulate rations, with grass hay added to dry cow and bull diets to achieve balanced diets. Emissions of CH_4 from stored manure were calculated according to the Intergovernmental Panel on Climate Change (IPCC, 2006) based on the quantity of volatile solids excreted, maximum CH_4-producing potential (0.24 m^3 per kg of volatile solids) and a CH_4 emission factor of 21.7% for liquid storage as reported by the US Environmental Protection Agency (US EPA, 2007). Manure N_2O was calculated according to IPCC (2006) emission factors for manure stored in liquid systems before spreading on cropland. Losses of N_2O from fertilizer application were also calculated according to IPCC (2006) guidelines using the most recent USDA-published application rates for corn (USDA/NASS, 2006) and soybeans (USDA/NASS, 2007), and estimates for alfalfa (Pimentel and Pimentel, 1996).

1944 Dairy Population Characteristics

Production practices and characteristics used within the 1944 dairy model were determined and validated by examination of scientific literature from 1935 to 1955. Additional sources included the annual USDA Yearbook of Agriculture series and extension bulletins from Cornell University and the Universities of Missouri, Minnesota, and Wisconsin (1940 to 1950). Modeling procedures were as described previously in Capper et al. (2008) with inputs adjusted for characteristics of 1944 production systems. The dairy cow population in 1944 comprised 54% small breeds (Jersey, Guernsey, Ayrshire) and 46% large breeds (Holstein, Brown Swiss) (http://www.agnr.umd.edu/DairyKnowledge/dairy/status_of_United_States_dairy_cattle.html). Two submodels based on milk yield and nutrient requirements for small or large breeds were therefore employed to estimate the environmental impact of the 2 groups, with the population results weighted accordingly for the proportion of each group within the total US herd. The average US milk yield/cow in 1944 was 2,074 kg/yr (http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats), adjusted for a 14-mo calving interval (426 d) and a 60-d dry period (VanDemark and Salisbury, 1950); this was equivalent to 5.6 kg/d for small breeds

and 7.8 kg/d for large breeds according to the Jersey-Holstein differential reported by Copeland (1939). Milk composition was characteristic of the breeds used, at 4.20% fat and 3.60% protein for small breeds, and 3.50% fat and 3.20% protein for large breeds (Davis et al., 1947). Lactating and dry cows averaged 45 mo of age, with BW of 439 kg (small breeds) or 610 kg (large breeds; Davis et al., 1943). Rations were formulated for replacement heifers at a median BW of 187 kg (small) or 255 kg (large) BW and with growth rates of 416 and 589 g/d for small and large breeds, respectively (Plum and Lush, 1934; Seath, 1940; Nevens, 1944). The number of heifers within the population were calculated using the existing model (Capper et al., 2008), modified for a 27-mo age at first calving (Bayley and Heizer, 1952), to give a ratio of 0.89 heifers/cow. Use of AI was rare in 1944, so all pregnancies were assumed to result from natural service. Bulls were therefore added to the population model at a ratio of 1 bull per 25 cows (Overton, 2005), with rations formulated (NRC, 2001) for 557 kg (small) and 774 kg (large) bulls at 45 mo of age. Adolescent replacement bulls were included in the population at a ratio of 0.89 replacements per adult bull, with rations formulated to fulfill nutrient requirements for small (238 kg of BW, 594 g/d growth rate) and large (330 kg of BW, 826 g/d growth rate) breeds. Pasture was the predominant forage source on dairy farms in the 1940s; therefore diets were formulated based on 40% of daily DMI from grass and the remainder from grass hay, corn, and soybean meal (Crandell and Turk, 1945). The nutrient composition of fresh pasture and hay was adjusted to reflect grass species of the time (Archibald et al., 1946), with reduced ME (7.5 MJ/kg of DM for grass, 6.9 MJ/kg of DM for hay) and CP (9.7% of DM for grass, 8.1% of DM for hay), and a digestibility coefficient of 55% for pasture (AFRC, 1996). Manure output was calculated according to diet digestibility, with a 15% DM content (Dado and Allen, 1995). Emissions of CH_4 and N_2O from manure were estimated as per the 2007 system using CH_4 emission factors of 1.5% (pasture) and 4.0% (solid storage), and N_2O emission factors of 0.02 kg of N_2O-N/kg for direct deposition onto pasture during grazing (IPCC, 2006). The model did not include N_2O emissions from inorganic fertilizers because these were not widely used in US agriculture until the late 1940s when ammonia synthesis technologies developed for ammunition production in World War II were adapted for agricultural chemical production (Smil, 2001).

Cropland Characteristics

Cropland requirements for both models were calculated using average US crop yields for 1944 (USDA/NASS, 2003) and 2007 (www.nass.usda.gov). Pasture-based US dairy production systems originally served to utilize land that was unsuitable for crop production due to characteristics such as unfavorable topography or soil type (Cardon et al., 1939). The majority of grazed and hayed grassland therefore functioned as permanent pasture, and there was no significant inflow of pasture or cropland into the system during the decade before 1944 (Cardon et al., 1939). For the purposes of this study, all pasture was considered to be permanent (i.e., present as pasture and undisturbed by tillage for >25 yr). In contrast to land recently converted from cropland to pasture, mature temperate pasture subject to biomass removal by grazing/haying (Skinner, 2008) or burning (Sukyer and Verma, 2001) is considered to have a net carbon balance close to zero. Conservation tillage systems were not widely practiced in the US until the mid-1970s; conventional (i.e., inversion) tillage was used for crop production in 1944, and this practice was assumed to been in place for >25 yr. Sequestration factors of zero for both pasture and cropland were therefore employed in the 1944 model, with appropriate multiplication factors to correct for manure inputs (IPCC, 2006). Crop management practices have undergone major changes over the past 30 yr, with increases in the quantity of land managed under conservation or no-till systems (Hobbs et al., 2007). Sequestration is a dynamic process that follows a logarithmic decay curve; therefore, quantifying the potential for changes in tillage practice at a particular point in time (i.e., 2007) is beyond the scope of this paper. However, it should be noted that by not including the carbon sequestration contributions made by conservation and the transition to no-till practices within modern production, the total carbon footprint for 2007 is overestimated. Within both models, water use was estimated only for the free water intake of the dairy population estimated according to Holter (1992).

Given the advances in technology and mechanization over the past 60 yr and a lack of available data, comparison of fuel requirements between the 2 systems was not possible. Nonetheless, the change in energy requirements incurred by shifting from draft horse to tractor power in the 1944 system was assessed. Energy requirements for a 2-horse team were calculated according to NRC (2007) based on 2 mature Clydesdale geldings under a moderate workload, each with a BW of 800 kg and a daily feed intake equal to 2% of BW. Rations were formulated based on grass hay, rolled barley, and rolled oats, and total cropland area calculated according to the average US crop yields from 1944 for each dietary component (USDA/NASS, 2003). Mechanical energy consumption was based on the maximum power take-off speed (29.6 hp) for a John Deere Series A tractor used in the equation developed for use in the Nebraska Tractor Test (Grisso et al., 2004) at average US usage of 434 tractor-hours/yr (Hertel and Williamson, 1940) and 34.6 MJ/L of gasoline.

RESULTS AND DISCUSSION

In 1944, the US dairy population totaled 25.6 million cows producing a total of 53.0 billion kg of milk annually (Figure 1; http://www.nass.usda.gov/Data_and_

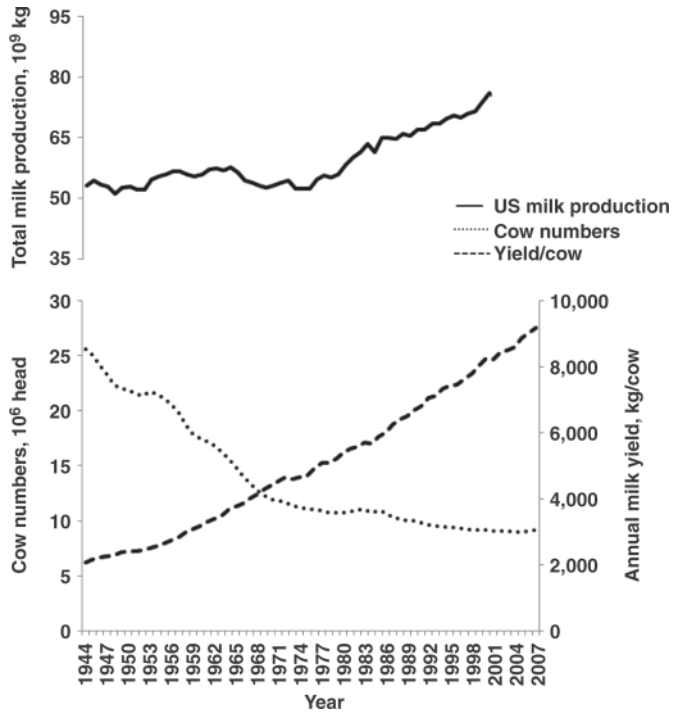

Figure 1. Changes in total US milk production, cow numbers, and individual cow milk yield between 1944 and 2007.

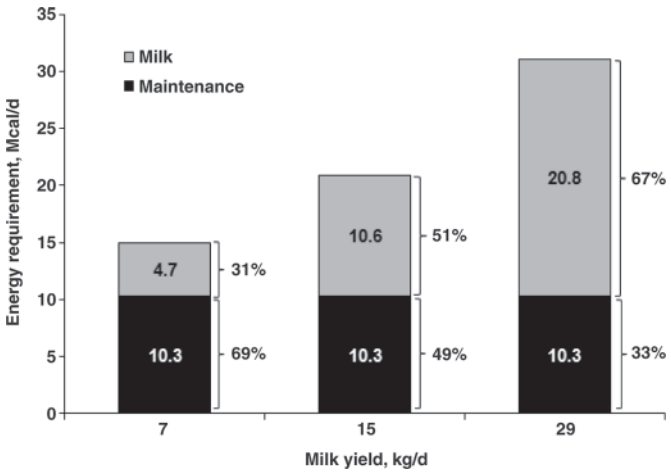

Figure 2. The dilution of maintenance effect conferred by increasing milk production in a lactating dairy cow (650 kg of BW, 3.69% milk fat).

Statistics/Quick_Stats). Dairy production in 1944 was characterized by pasture-based systems with rations reliant on home-grown forages with few purchased concentrate feeds (Woodward, 1939). Draft horses powered the majority of agronomical operations, with only 1.2 tractors employed per farm (US Census Bureau, 1950). Inorganic fertilizer use was not yet widespread; instead, animal manure was used to fulfill crop nutrient requirements (Yeck, 1981; Hoban, 1997). Interestingly, many of these characteristics (low-yielding, pasture-based, no antibiotics, inorganic fertilizers, or chemical pesticides) are similar to those of modern organic systems. By contrast, the 2007 US dairy herd comprised only 9.2 million cows, with an annual milk production of 84.2 billion kg (Figure 1). Typical modern dairy production systems are characterized by the use of total mixed rations formulated to fulfill nutrient requirements, together with herd health and management programs and facilities designed to minimize stress and maximize production (USDA, 2007). Furthermore, feedstuffs used in modern systems are harvested from high intensity row-crop farming practices.

All food production systems have an environmental impact, which must be assessed per unit of output (i.e., kg of milk or loaf of bread). Within the dairy industry, from production through retail sales, the majority (80 to 95%) of global warming, eutrophication, and acidification potentials occur during the on-farm production phase (Berlin, 2002; Høgaas Eide, 2002). Consequently, our production system model includes all primary crop and milk production practices integrated into the process of life cycle assessment up through and including milk harvest, and does not include any transportation, processing, or sales system parameters post-milk harvest. Accurate evaluation allows quantification of the impact of technologies and management practices that improve productive efficiency, defined as "units of milk produced per unit of resource input" (Capper et al., 2008). The importance of improving productive efficiency as a foundation to provide sufficient food for the increasing US population was recognized as early as 1927 (McDowell, 1927); however, it was only made possible by specialization and intensification of agricultural production after World War II. Average milk yield per cow in 1944 was 2,074 kg/y, compared with 9,193 kg in 2007. This improvement in productive efficiency facilitates the dilution of maintenance effect, by which the total resource cost per unit of milk is reduced (Bauman et al., 1985). The daily nutrient requirement of lactating cows comprises a specific quantity needed to maintain the vital functions and minimum activities in a thermo-neutral environment (maintenance requirement) of the animal plus extra nutrients to support the cost of lactation. As shown in Figure 2, the maintenance energy requirement does not change as a function of production, but the daily energy requirement increases as milk yield increases, thereby reducing the proportion of total energy used for maintenance. The total energy requirement per kg of milk produced is therefore reduced: a cow producing 7 kg/d requires 2.2 Mcal/kg of milk, whereas a cow yielding 29 kg/d needs only 1.1 Mcal/kg of milk (Figure 2).

Improved productive efficiency enables greater milk yields, thus meeting market demand for milk using fewer cows (Capper et al., 2008). Indeed, the dairy population required to produce 1 billion kg of milk in 2007 was only 21% of that required in 1944 (Table 2). Genetic improvement has been a major contributor to this increase in productivity. Three factors have played into the genetic change. First, the most common dairy breeds have shifted from the high milk-solids breeds (e.g., Jersey, Guernsey) to the greater-volume producing Holstein cow. Holstein cows comprised only 39%

Table 2. Comparison of resource inputs, waste output, and environmental impact of dairy production systems in 1944 and 2007

Variable	1944	2007
Milk produced, billion kg	53.1	84.2
	Resources/waste per billion kg milk produced	
Animals, n		
Lactating cows, $\times 10^3$	414.8	93.6
Dry cows, $\times 10^3$	67.4	15.2
Heifers, $\times 10^3$	429.2	90.3
Mature bulls, $\times 10^3$	19.29	1.31
Adolescent bulls, $\times 10^3$	17.17	1.08
Total population, $\times 10^3$	948	202
Nutrition resources		
Maintenance energy requirement,[1] MJ $\times 10^9$	16.66	3.87
Maintenance protein requirement,[1] kg $\times 10^6$	165.4	48.4
Feedstuffs, kg of freshweight $\times 10^9$	8.26	1.88
Land, ha $\times 10^3$	1,705	162
Water, L $\times 10^9$	10.76	3.79
Waste output		
Nitrogen excretion, kg $\times 10^6$	17.47	7.91
Phosphorus excretion, kg $\times 10^6$	11.21	3.31
Manure, freshweight, kg $\times 10^9$	7.86	1.91
Gas emissions		
Methane,[2] kg $\times 10^6$	61.8	26.8
Nitrous oxide,[3] kg $\times 10^3$	412	230
Carbon footprint,[4] kg of $CO_2 \times 10^9$	3.66	1.35

[1]Refers to nutrients required for maintenance (all animals), pregnancy (dry cows), and growth (heifers and adolescent bulls).

[2]Includes CH_4 emissions from enteric fermentation and manure.

[3]Includes N_2O emissions from manure (both years) and from inorganic fertilizer application (2007 only).

[4]Includes CO_2 emissions from animals, plus CO_2 equivalents from CH_4 and N_2O.

of the US dairy herd in 1944 (http://www.agnr.umd.edu/DairyKnowledge/dairy/status_of_United_States_dairy_cattle.html) compared with 90% in 2007 (USDA, 2007). Second, AI has been widely adopted since the 1970s (Weimar and Blayney, 1994). Finally, improved genetic evaluation procedures have greatly enhanced the ability to identify and select animals that are genetically superior for milk production. Shook (2006) estimated that of the 3,500 kg increase in lactation yields since 1980, 55% can be attributed to improved genetics. This agrees with published USDA-ARS-AIPL data dating back to 1960 (http://aipl.arsusda.gov/eval/summary/trend.cfm). The combined effect of AI adoption and genetic improvement has had a 2-fold impact on the number of dairy animals required to produce 1 billion kg of milk. Increasing milk yields through genetic enhancement reduced the number of cows, and the advent of frozen semen use in AI severely curtailed the number of bulls, as one sire was able to successfully breed many more cows than a natural service sire. The nutrients required to maintain the dairy population have therefore been reduced. The 1944 production system required 16.7 billion MJ of ME and 165 million kg of CP per billion kg of milk produced, whereas the 2007 system required 3.9 billion MJ of energy and 48 million kg of CP (Table 2).

The first National Research Council report regarding the nutrient requirements for dairy cows was published in 1945, allowing for considerable improvement in formulating diets targeted to specific animal requirements (NRC, 1945). Furthermore, introduction of ration-formulation software and widespread acceptance of total mixed rations in the 1980s (Weimar and Blayney, 1994) allowed dairy producers to improve nutrient supply from diets and include greater amounts of by-products from human food and fiber industries (Van Horn et al., 1996). The reduction in feedstuff use per billion kilograms of milk in 2007 compared with 1944 not only reflects the reduced population size but is also a function of the improved nutritive value of feedstuffs fed in modern dairy systems, providing more nutrient-dense rations (Archibald et al., 1946; NRC, 2001). Pasture-based systems employed in 1944 required considerably more land to support the dairy population, both for grazing and production of hay and cereal crops. The recommended stocking rate for lactating dairy cows in the 1940s was 1 cow/ha (Henderson and Reaves, 1954) compared with 2.3 cows/ha for modern systems (McCall and Clark, 1999), reflecting the reduced yield and nutritive value of native grass pastures compared with modern grass species. Furthermore, advances made in crop genetics (e.g., trait selection in hybrid seed, Bt corn, herbicide-resistant soybeans), agronomy (e.g., minimum and no-till systems), and nutrition (e.g., soil testing, application of inorganic fertilizers) between 1944 and 2007 have resulted in a corn grain yield in-

crease from 2,071 to 9,484 kg/ha, and a soybean yield increase from 1,264 to 2,804 kg/ha (USDA/NASS, 2003); http://www.nass.usda.gov). Improved efficiency of both milk and crop production has therefore reduced the amount of cropland needed to support the production of 1 billion kg of milk to 162,000 ha: 10% of the land required in 1944.

Pasture grass species employed within 1944 dairy production included Kentucky bluegrass, timothy, and orchard grass (Cardon et al., 1939) with reduced protein contents than modern varieties (Huffman, 1939). Consequently, N intake per animal was considerably less and the index for N excretion somewhat less than would be predicted from the extrapolation of animal numbers from 1944 to 2007 (Table 2). Despite the capacity of the 1944 system to have a greater transfer of nutrients (N and P) into groundwater, it is interesting to note that historical manure management practices had a slight mitigating effect upon CH_4 production. This is directly attributable to differences in manure storage; according to IPCC (2006), the 1944 production system, with cows spending equal time grazing and housed, would have an average methane conversion factor of 2.75% of excreted N (1.5% while grazing and 4.0% for solid manure storage) compared with 21.7% for modern lagoon-storage. However, this advantage was negated by the 1944 population size, which resulted in increased total production of CH_4 and N_2O from enteric fermentation and manure.

A recent report from the Food and Agriculture Organization (Steinfeld et al., 2006) concludes that livestock are responsible for 18% of global anthropogenic greenhouse gas (**GHG**) emissions. This statistic needs to be applied in the correct context and is not representative of US agriculture. Deforestation for pasture and cropland is a major contributor to global carbon dioxide emissions and has been exacerbated by the use of formerly food-producing agricultural land to grow biofuel crops (Sawyer, 2008). However, the majority of US feedstuffs are produced domestically, with increased crop yields compensating for a reduction in available cropland. Furthermore, the global figure of the FAO includes a significant contribution from extensive livestock systems producing meat or milk at very low efficiencies, thus considerably inflating the GHG output per unit of food. The effect of improved agricultural production efficiency is reinforced by figures from the US Environmental Protection Agency (US EPA, 2008) estimating that only 6.4% (454 teragrams CO_2-equivalents) of national GHG emissions arise from agriculture. Dairy production is only responsible for 11.5% (52 teragrams CO_2-equivalents) of this figure, resulting in a total contribution of <1% to US GHG emissions.

Improved productive efficiency demonstrably reduces the GHG emissions and overall environmental impact of dairy production (Capper et al., 2008). The ultimate goal of the dairy system is to supply sufficient milk to satisfy both the requirements of the US population and export demand, and thus environmental impact should

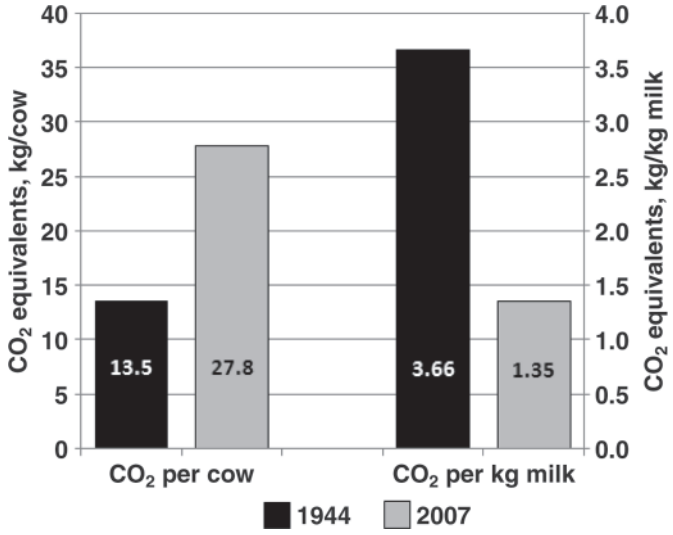

Figure 3. Carbon footprint per cow and per kilogram of milk for 1944 and 2007 US dairy production systems. The carbon footprint per kilogram of milk includes all sources of greenhouse gas emissions from milk production including animals, cropping, fertilizer, and manure.

be quantified per unit of milk produced. Nonetheless, estimates of environmental impact are often quoted per animal or per unit of land. The increased carbon footprint of an average 2007 cow compared with its 1944 equivalent (Figure 3) appears to prove the argument that modern-day intensive productive practices are less environmentally sustainable than their 1944 equivalents and that it would be beneficial to return to the husbandry systems practiced 60 yr ago. However, when expressed on an outcome basis (per kg of milk; Figure 3), the carbon footprint per kg of milk in 2007 is only 37% of that in 1944. Accounting for the increased use of by-products from the human food and fiber industries within modern dairy production would further reduce the carbon footprint of milk production in 2007. Despite the paucity of data relating to fossil fuel inputs, it is possible to estimate the relative magnitude of the industry carbon footprint based on total milk production when comparing these 2 yr. The total carbon footprint for the 1944 dairy industry was 194 million metric tonnes of CO_2-equivalents compared with 114 million metric tonnes of CO_2–equivalents for 2007. This 41% reduction in the carbon footprint of the modern system compared with the 1944 system, taken in conjunction with the greater total milk supply, underlines the importance of improved productive efficiency in reducing the environmental impact of dairy production.

The shift from the draft animal-powered agronomy of the first half of the twentieth century to the highly mechanized operations practiced today is characterized by a more efficient use of labor and time, but is difficult to evaluate on a GHG emission basis. Nonetheless, in an effort to quantify the difference in fossil fuel input between the 2 systems we have characterized the primary means of work energy within the 2 time periods. Interestingly, energetic inputs associated with fulfilling the requirements of a team of draft animals under

Table 3. Annual energy requirements for a team of draft horses vs. a 30-horsepower (hp) tractor characteristic of 1944 dairy production systems

Resource use	Team of draft horses[1]	30-hp tractor[2]
Annual energy requirement, MJ	1.14×10^5	1.02×10^5
Cropland required to support horses,[3] ha	7.34	—
Gasoline equivalent, L	—	2.93×10^3

[1]Based on 2 × 800 kg Clydesdales eating 2% BW/d of hay-oat-barley ration formulated for moderate work (NRC, 2007).

[2]Calculated from technical specification for John Deere series A, 29.6 max hp from PTO shaft, 434 tractor h/yr (Hertel and Williamson, 1940).

[3]Cropland required to produce sufficient feed under 1944 conditions (USDA/NASS, 2003).

moderate work were 12% greater than the equivalent energy cost of the same work supplied by tractor power (Table 3). In an analysis of fossil fuel usage on US farms, Cleveland (1995) demonstrated that the ratio of on-farm productivity to energy use declined from 1910 to 1970 and attributes this to inefficiency promoted by low fuel costs. This trend reversed as intensification, farm sizes, and fuel costs increased in the 1970s, and these factors are likely to further improve energy productivity in future (Cleveland, 1995). Rydberg and Jansen (2002) noted that although man-hours and energy use are considerably reduced when using modern tractors compared with horse traction, the majority (91%) of energy inputs to the tractor-based system originate from nonrenewable fossil fuels, whereas 60% of draft energy inputs are renewable. Thus, not only energy efficiency, but also energy source must be considered when evaluating the environmental impact of agricultural practices.

Remarkable advances have been made in dairy production over the past 60 yr with demonstrable increases in productive efficiency conferred by genetic selection, ration formulation, preventative health programs, improved cow comfort, and better management practices (Eastridge, 2006; LeBlanc et al., 2006; Shook, 2006). This is underlined by the ability of modern dairy cows to produce considerably more milk than their historical counterparts through improved welfare and reduced disease incidence (LeBlanc et al., 2006). It is also clear that the environmental impact of the modern US dairy production system is considerably less than that of the historical system with substantial reductions in resource use (feedstuffs, crop land, energy, and water), waste output (manure, N, and P excretion), and GHG emissions. Contrary to the negative image often associated with "factory farms," fulfilling the requirement for dairy products of the US population while improving environmental stewardship can only be achieved by using modern agricultural techniques. The immediate challenge for the dairy industry is to actively communicate the gains made since World War II and the considerable potential for environmental mitigation yet to be gained through use of modern dairy production systems.

LITERATURE CITED

AFRC. 1996. Energy and Protein Requirements of Ruminants. CAB Int., Wallingford, UK.

Archibald, J. G., E. Bennett, and J. W. Kuzmeski. 1946. Some observations on "quality" in hays. J. Dairy Sci. 29:795–800.

Bauman, D. E., S. N. McCutcheon, W. D. Steinhour, P. J. Eppard, and S. J. Sechen. 1985. Sources of variation and prospects for improvement of productive efficiency in the dairy cow: a review. J. Anim. Sci. 60:583–592.

Bayley, N. D., and E. E. Heizer. 1952. Herd data measures of the effect of certain environmental influences on dairy cattle production. J. Dairy Sci. 35:540–549.

Berlin, J. 2002. Environmental life cycle assessment (LCA) of Swedish hard cheese. Int. Dairy J. 12:939–953.

Capper, J. L., E. Castañeda-Gutiérrez, R. A. Cady, and D. E. Bauman. 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. Proc. Natl. Acad. Sci. USA 105:9668–9673.

Cardon, P. V., W. R. Chapline, T. E. Woodward, E. W. McComas, and C. R. Enlow. 1939. Pasture and Range in Livestock Feeding. Page 925 in Yearbook of Agriculture, 1939. USDA, Washington, DC.

Cleveland, C. J. 1995. The direct and indirect use of fossil fuels and electricity in USA agriculture, 1910–1990. Agric. Ecosyst. Environ. 55:111–121.

Copeland, L. 1939. A study of factors concerning herd management and herd production. J. Dairy Sci. 22:229–239.

Crandell, W. T., and K. L. Turk. 1945. Feeding the Dairy Cow Efficiently. Cornell Extension Bulletin 363. Ithaca, NY.

Dado, R. G., and M. S. Allen. 1995. Intake limitations, feeding behavior, and rumen function of cows challenged with rumen fill from dietary bulk or inert fiber. J. Dairy Sci. 78:118–133.

Davis, R. N., F. G. Harland, A. B. Caster, and R. H. Kellner. 1947. Variation in the constituents of milk under Arizona conditions. III. Variation in milk from Jersey, Guernsey, Holstein, and mixed herds. J. Dairy Sci. 30:435–442.

Davis, R. N., R. F. Morgan, and W. L. Gaines. 1943. Live weight and milk-energy yield in the Nebraska Station dairy herd. J. Dairy Sci. 26:625–641.

De Vries, A., M. Overton, J. Fetrow, K. Leslie, S. Eicker, and G. Rogers. 2008. Exploring the impact of sexed semen on the structure of the dairy industry. J. Dairy Sci. 91:847–856.

Eastridge, M. L. 2006. Major advances in applied dairy nutrition. J. Dairy Sci. 89:1311–1323.

Grisso, R., M. F. Kocher, and D. H. Vaughan. 2004. Predicting Tractor Fuel Consumption. Appl. Eng. Agric. 20:553–561.

Henderson, H. O., and P. M. Reaves. 1954. Dairy Cattle Feeding and Management. 4th ed. John Wiley & Sons, New York, NY.

Hertel, J. P., and P. Williamson. 1940. Costs of Farm Power and Equipment. Cornell Extension Bulletin 751. Ithaca, NY.

Hoban, T. J. 1997. Consumer acceptance of biotechnology: An international perspective. Nat. Biotechnol. 15:232–234.

HobbsP. R.SayreK.GuptaR.. 2007. The role of conservation agriculture in sustainable agriculture. Philos. T. Roy. Soc. B. 363:543–555.

Høgaas Eide, M. 2002. Life cycle assessment of industrial milk production. Int. J. Life Cycle Assess. 7:115–126.

Holter, J. B. 1992. Water partitioning and intake prediction in dry and lactating Holstein cows. J. Dairy Sci. 75:1472–1479.

Huffman, C. F. 1939. Roughage quality and quantity in the dairy ration, a review. J. Dairy Sci. 22:882–980.

IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies (IGES) for the IPCC, Kanagawa, Japan.

LeBlanc, S. J., K. D. Lissemore, D. F. Kelton, T. F. Duffield, and K. E. Leslie. 2006. Major advances in disease prevention in dairy cattle. J. Dairy Sci. 89:1267–1279.

McCall, D. G., and D. A. Clark. 1999. Optimized dairy grazing systems in the Northeast United States and New Zealand. II. System Analysis. J. Dairy Sci. 82:1808–1816.

McDowell, J. C. 1927. Dairyman's slogan should be "Not more, but better animals". Page 268 in Yearbook of Agriculture. USDA, Washington, DC.

Meigs, E. B. 1939. The feeding of dairy cows for intensive milk production in practice. Page 566 in Yearbook of Agriculture. USDA, Washington, DC.

Mowrey, A., and J. N. Spain. 1999. Results of a nationwide survey to determine feedstuffs fed to lactating dairy cows. J. Dairy Sci. 82:445–451.

Nevens, W. B. 1944. Live-weight gains of pasture-fed heifers. J. Dairy Sci. 27:1011–1014.

NRC. 1945. Recommended Nutrient Allowances for Dairy Cattle. Natl. Acad. Press, Washington, DC.

NRC. 2001. Nutrient Requirements of Dairy Cattle. Natl. Acad. Press, Washington, DC.

NRC. 2007. Nutrient Requirements of Horses. Natl. Acad. Press, Washington, DC.

Overton, M. W. 2005. Cost comparison of natural service sires and artificial insemination for dairy cattle reproductive management. Theriogenology 64:589–602.

Pimentel, A., and M. Pimentel. 1996. Food Energy and Society. University Press of Colorado, Boulder, CO.

Plum, M., and J. L. Lush. 1934. Freshening ages of purebred cows in Iowa cow testing associations. J. Dairy Sci. 17:625–638.

Rydberg, T., and J. Jansen. 2002. Comparison of horse and tractor traction using emergy analysis. Ecol. Eng. 19:13–28.

Sawyer, D. 2008. Climate change, biofuels and eco-social impacts in the Brazilian Amazon and Cerrado. Philos. T. Roy. Soc. B. 363:1747–1752.

Seath, D. M. 1940. The intensity and kind of selection actually practiced in dairy herds. J. Dairy Sci. 23:931–951.

Shook, G. E. 2006. Major advances in determining appropriate selection goals. J. Dairy Sci. 89:1349–1361.

Skinner, R. H. 2008. High biomass removal limits carbon sequestration potential of mature temperate plants. J. Environ. Qual. 37:1319–1326.

Smil, V. 2001. Enriching the Earth: Fritz Haber, Carl Bosch and the Transformation of World Food Production. The MIT Press, Cambridge, Massachusetts.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. de Haan. 2006. Livestock's Long Shadow - Environmental Issues and Options. Food and Agriculture Organization of the United Nations, Rome, Italy.

Sukyer, A. E., and S. B. Verma. 2001. Year-round observations of the net ecosystem exchange of carbon dioxide in a native tallgrass prairie. Glob. Change Biol. 7:279–289.

U.S. Census Bureau. 1950. Census of Agriculture, 1950. US Census Bureau, Washington, DC.

US EPA. 2007. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2005. Annex 3: Methodological Descriptions for Additional Source or Sink Categories. US Environ. Protection Agency, Washington, DC.

US EPA. 2008. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006. US Environ. Protection Agency, Washington, DC.

USDA. 2007. Dairy 2007, Part I: Reference of Dairy Cattle Health and Management Practices in the United States, 2007. USDA-APHIS-VS, Fort Collins, CO.

USDA/AMS. 2007. Federal Milk Order Market Statistics 2006. USDA, Washington DC.

USDA/NASS. 2003. Historical Track Records. USDA/NASS, Washington, DC.

USDA/NASS. 2006. Agricultural Chemical Usage 2005 Field Crops Summary. USDA-NASS, Washington, DC.

USDA/NASS. 2007. Agricultural Chemical Usage 2006 Field Crops Summary. USDA-NASS, Washington, DC.

Van Horn, H. H., G. L. Newton, and W. E. Kunkle. 1996. Ruminant nutrition from an environmental perspective: Factors affecting whole-farm nutrient balance. J. Anim. Sci. 74:3082–3102.

VandeHaar, M. J., and N. St-Pierre. 2006. Major advances in nutrition: Relevance to the sustainability of the dairy industry. J. Dairy Sci. 89:1280–1291.

VanDemark, N. L., and G. W. Salisbury. 1950. The relation of the post-partum breeding interval to breeding efficiency in the dairy cow. J. Anim. Sci. 9:307–313.

Weimar, M. R., and D. P. Blayney. 1994. Landmarks in the U.S. Dairy Industry. Agriculture Information Bulletin No. 694. ERS/USDA, Washington, DC.

Woodward, T. E. 1939. Figuring the rations of dairy cows. Page 592 in Yearbook of Agriculture. USDA, Washington, DC.

Yeck, R. G. 1981. Managing dairy wastes. J. Dairy Sci. 64:1358–1364.