Efficiency of Dairy Production and its Carbon Footprint[2,3]

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Introduction

The productivity of the American farmer has increased dramatically over the last century. One hundred years ago a farmer produced enough to feed 15 people and over 40% of the US population was involved in agriculture-related businesses. Today the produce from an average farmer feeds 130 people and farmers represent less than 2% of the U.S. population. The increases in agricultural productivity over the last century have provided the opportunity for our population to pursue the wide range in vocations and lifestyles that we enjoy today. Sustainability is a more recent concept and it is often defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (UN/WCED, 1987). Thus, the application of sustainable agricultural practices that maximize efficiency to produce more food with fewer resources is critical to ensure the balance between present and future needs so that our natural resources are protected for future generations. There are many dimensions to sustainability (Sapp et al., 2009). Indeed, Arnot (2009) emphasized that public confidence in a sustainable agricultural system requires it be economically viable, scientifically verified, and ethically grounded.

A sustainable agriculture system must produce nutritious and safe foods that are accessible and affordable. All food has an environmental impact, regardless of the production system, and a sustainable agricultural system must meet food needs while minimizing social, economic and environmental impact. As we look toward the future, achieving food security will be a major challenge because the world population is estimated to increase from the present 6.7 billion to over 9.5 billion by the year 2050

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(US Census Bureau, 2008). The combination of predicted increases in population size and affluence is calculated to double current food requirements by the year 2050.

Resources are limited and the U.N Food and Agriculture Organization estimates that 70% of the additional food supply must come from the development and use of efficiency-enhancing technologies (UN/WHO, 2002).

The importance of animal-derived foods in meeting the food security needs of the global population is well recognized (Murphy and Allen, 2003; Randolph et al., 2007). Animal-derived foods represent an important source of energy, protein, and micronutritents including many essential minerals and vitamins. Dairy products contribute significant amounts of 4 of 7 “nutrients of concern” identified by the recent Dietary Guidelines for Americans as being deficient in adult diets, and 3 of 5 nutrients of concern in children’s diets (USDA, 2005, Huth et al., 2008). Furthermore, animal protein is of higher nutritional quality than plant protein sources because of its ideal balance of essential amino acids. (Hegsted and Chang, 1965). The nutrient composition of foods is therefore a consideration in developing a sustainable agricultural system (Fulgoni et al., 2009).

Productive Efficiency and the ‘Dilution of Maintenance’ Effect

Increases in productivity provide clear evidence of the many changes the dairy industry has undergone over the last century. One hundred years ago the average milk production of a dairy cow was less than 5 kg/d and the average farm was diversified and had less than 5 cows. This contrasts with the specialization of the modern dairy industry were cows have a lactational average milk production of ~30 kg/d and almost 60% of the milk supply comes from dairy farms with over 500 cows (USDA, 2007). These gains in milk production per cow over the last century are due to increases in our understanding of the biology of the dairy cow and the application of this knowledge to develop new technologies and improve management practices. Thus, the dairy industry has achieved an increase in the milk production potential of the dairy cow while implementing technologies and management practices that allow the cow to achieve that potential.

The phenomenal increases in milk production allow the production of a gallon of milk from fewer nutrients and less animal waste. Improving ‘productive efficiency’ (milk output per resource inputs) is the mechanism by which a dairy herd can mitigate environmental impact. Producing more milk from the same quantity of resources (or the same amount of milk with fewer resources) reduces the demand for non-renewable or energy-intensive inputs (e.g. land, water, fossil fuels and fertilizers) and promotes environmental stewardship.

The biological processes underlying improved productive efficiency is known as the ‘dilution of maintenance’ effect (Bauman et al., 1985; VandeHaar and St-Pierre, 2006). A lactating dairy cow requires daily nutrients for maintenance and for milk synthesis. The maintenance requirement does not change with production level and therefore can be thought of as a fixed cost needed to maintain vital functions. As shown in the Figure 1, the maintenance energy requirement for a 650 kg cow is 10.3 Mcal/d. Assuming milk composition remains constant, the nutrient requirement per unit of milk production also does not change, but the total energy cost for lactation increases as a function of milk production. It can therefore be thought of as a 'variable cost' of dairy production. A high-producing dairy cow requires more nutrients per day than a low-producing dairy cow, but in our example the cow with a daily milk output of 29 kg is using only 33% of consumed energy for maintenance whereas the low producing cow (7 kg/d) is using 69% of energy intake for the maintenance (Figure 1). Increased production thus dilutes out the fixed cost (maintenance) over more units of milk production, reducing the total energy requirement per kg of milk output. A cow producing 7 kg/d requires 2.2 Mcal/kg milk, whereas a cow yielding 29 kg/d needs only 1.1 Mcal/kg milk.

At first glance, the above concept seems counterintuitive: if high-producing cows are eating more feed, they are consuming more resources and emitting more waste products, all of which are environmental concerns. In fact, the guest on a recent National Public Radio program was extolling the environmental virtues of low input agriculture. This is also a message that is often propounded by anti-animal agriculture groups, but it is both misleading and inaccurate. Accurate and complete evaluation of the environmental effects of dairy production requires a paradigm shift. The majority of studies to date have examined the resource input and waste output for an individual cow and multiplied this figure by the number of animals within the herd or national population to estimate the system impact. This method has several limitations. This approach only examines one aspect of the milk production process, i.e. the lactating cow, and ignores the resources required to support the entire dairy population (lactating cows plus associated dry cows, heifer replacements and bulls) that are necessary to maintain the milk production infrastructure. Alternatively, data have been presented according to land use, e.g. per acre or hectare. The major flaw of this basis of expression is that environmental impact thus varies according to stocking rate, with extensive systems appearing to be superior to their intensive counterparts, regardless of the total amount of land required for food production.

The ultimate purpose of a sustainable dairy industry is to produce sufficient milk to supply the human population. Environmental impact must, therefore, be assessed on per unit of food produced, i.e. per kg of milk or dairy product. This methodology allows valid comparisons to be made among different production systems and also relates milk production to demand, facilitating accurate evaluation of the resources required to fulfill human food requirements. Utilizing values from Figure 1, one can calculate that to produce a set amount of milk, e.g. 29,000 kg/d, would require 4,143 low-producing cows (7 kg/d), but only 1,000 high-producing cows (29 kg/d). When the remainder of the dairy population is taken into account, it can be seen that the dilution of maintenance effect not only reduces the number of milking cows required to achieve a given production, but also decreases the associated dry cows, heifers and bulls within the population and the resources required to maintain that population.

Productive Efficiency – The Historical Example

The dairy industry has made impressive advances in productivity over the past 65 years: a comparison of 1944 with 2007 provides a clear example of the environmental impact of gains in productive efficiency (Capper et al., 2009). Cow numbers in the U.S. peaked in 1944 at 25.6 million head with a total milk production of 53 billion kg (http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/). In contrast, there were 9.2 million cows in the 2007 US dairy herd producing a total of 84 billion kg of milk. Thus, there was a four-fold increase in the annual milk yield per cow, progressing from 2,074 kg/cow in 1944 to 9,193 kg/cow in 2007. This improvement has been achieved through the introduction of production and management practices that maximize potential yields while emphasizing cow health and welfare. For example, widespread adoption of genetic evaluation and artificial insemination in the late 1960's allowed producers to select the highest-yielding cows and thereby improve the genetic merit of the current and future herd. These technologies have conferred approximately 55% of the annual milk yield increase since 1980 (Shook, 2006). Nutrition-related advances have been of particular significance in allowing cows to achieve their genetic potential and these include defining nutrient requirements, developing feed analyses methods, and using this information to formulate diets that meet these requirements (Eastridge, 2006). In the 1970's the use of total mixed rations became widespread and more recently the use of diet formulation software have further facilitated feeding a ration balanced according to milk production and nutrient needs. Progress has also occurred as a result of better milking management systems and mastitis control, implementation of herd health and preventative medicine programs, improved cow comfort (including housing and heat stress abatement) and the use of biotechnologies and feed additives that maximize milk production.

A common consumer perception is that historical methods of food production were inherently more environmentally-friendly than modern agricultural systems, often referred to as 'factory farms'. This is frequently reinforced with a vision of the 'good old days' where cows grazed peacefully on a lush green hillside with the red hip-roof barn off in the distance. But how do the good old days actually compare? We used a life cycle assessment (LCA) model to quantify the environmental impact of 1944 compared to 2007 (Capper et al., 2009). On an individual basis, the low-producing cow of 1944 had a much lower carbon footprint than the modern high-producing dairy cow (Figure 2). At first glance, this appears to support the concept that the good old days were more environmentally friendly. However, when data are expressed correctly, i.e. per unit of milk, the advantage from the improvements in productive efficiency of modern milk production is striking. The carbon footprint of a gallon of milk produced in 2007 is only 37% of what it was in 1944 (Figure 2).

The marked reduction in the carbon footprint of milk production represents a remarkable success story for the dairy industry, and this should be noted in discussions of the environmental impact of animal agriculture. The productive efficiency gains between 1944 and 2007 have a major impact on dairy system sustainability as shown in

Figure 3. Compared to 1944, the production of an equal quantity of milk in 2007 requires only 21% of the animals, 23% as much feed, 35% of the water, 10% of the land area and produces only 24% as much animal waste. Particularly impressive is a comparison of the total dairy industry; in 2007 the U.S. dairy industry produced 59% more milk with a total carbon footprint 41% less than the 1944 industry (Figure 3). Today's dairy cows have a much greater genetic potential for milk production, but it's noteworthy that modern organic systems have many of the characteristics of 1940's dairy production. Organic systems are lower-yielding, pasture-based and do not use antibiotics to treat ill animals, hormones in reproductive programs, inorganic fertilizers or chemical pesticides. Indeed, studies evaluating the environmental impact of organic systems have reported that the quantity of resources required and the carbon footprint per kg of milk are greater in organic production compared to conventional dairy systems (Capper et al., 2008, de Boer, 2003, Williams et al., 2006).

Productive Efficiency – The Technology Example

Dairy producers are being encouraged to adopt management practices that facilitate improved environmental stewardship and conservation at all stages of the milk production process. These initiatives to improve sustainability of the dairy system include cutting greenhouse gas (GHG) emissions through reducing enteric methane production (Anderson et al., 2003; Beauchemin et al., 2008), minimizing nutrient run-off by effective ration balancing and optimizing fertilizer application (Dittert et al., 2005, James et al., 1999, Rotz, 2004), and harnessing the potential for methane generated from waste to be converted for on-farm energy use (Cantrell et al., 2008). No single management practice has the ability to negate the environmental impact of dairy production, although considerable improvements can be made following the adoption of several co-existing strategies. Nonetheless, adopting technologies and management practices that improve productive efficiency may have the greatest effect on mitigating the environmental effect.

Increases in productive efficiency have been the engine fueling growth in agricultural productivity over the last century (Ball and Norton, 2002). However, some consumers have a negative image of technology and regard the use of agricultural technologies such as genetic modification, antibiotics and hormones as unnatural and threats to humans and animals despite assurances from reputable health organizations and government agencies. The introduction of artificial insemination is a case in point, with claims that its use would result in an 'inferior, decadent, degenerative species' (of cow) and that milk was unsuitable for human consumption (Tobe, 1967). Likewise, those opposing FDA approval of recombinant bovine somatotropin (rbST) claimed it would cause cancer and AIDS-like disease in humans, pus and antibiotics in milk, and hypermetabolic syndrome and burnout in cows (Bauman, 1999). Nonetheless, the use of agricultural technologies provides an invaluable opportunity to improve production, with concurrent effects upon environmental impact. For example, transgenic seeds are currently used in 80-90% of the U.S. production of corn and soybeans. The widespread adoption of genetically modified Bt-corn has significantly increased US corn yields

(NCFAP, 2008) and the introduction of herbicide-resistant soybeans has not only improved yields, but also facilitated the use of no-till practices, thus reducing soil erosion, carbon loss and fossil fuel use (Hobbs et al., 2007).

The use of rbST provides an example to examine the environmental effect of a specific dairy technology. Over 30 million U.S. dairy cows have received rbST since its approval by the FDA in 1994, and its use has arguably provided the greatest technological contribution to improved dairy productivity. The milk yield response to rbST supplementation is well-documented, and its potential as a tool to improve productive efficiency and thus reduce the environmental impact of dairy production has been enumerated in national reports (National Research Council, U.S. Congress and Environmental Protection Agency) and a series of scientific publications (Bauman, 1992; Bosch et al., 2006; Dunlap et al., 2000; Johnson et al*.,* 1992; Jonker et al., 2002).. More recently we developed a deterministic model based on nutrient requirements (NRC, 2001) and used a science-based LCA to more completely evaluate the environmental impact of rbST (Capper et al., 2008).

The environmental impact of rbST use in one million cows is shown in Table 1. Annual milk production from the rbST-supplemented population (2.51 million animals in total) was 14.1 billion kg; however, to produce the same amount of milk from an unsupplemented population would require an extra 157,000 milking cows and 177,000 associated dry cows and heifers. The rbST-supplemented population therefore requires fewer resources, including 2.3 million metric tonnes less feedstuffs, 540,000 less acres of land for crop production (with concurrent reductions in soil erosion) and considerable savings in fertilizers and pesticides. Reducing resource input per unit of milk demonstrates the improved productive efficiency conferred by rbST use, and this also has beneficial environmental effects. Using a smaller population to maintain an equivalent milk production decreases total manure production, thus releasing less methane and nitrous oxide (two extremely potent GHG) into the atmosphere. As noted by Jonker et al. (2002) and Dunlap et al. (2000), decreasing population manure production via rbST use reduces potential nutrient (N and P) flows into groundwater.

Consumption of non-renewable energy sources is a significant issue for a sustainable dairy system as fossil fuel combustion not only depletes existing deposits, but also increases the industry's carbon footprint (Table 1). By improving productive efficiency, rbST-supplementation of one million cows reduces annual fossil fuel and electricity use by 729 million MJ and 156 million kWh, respectively; equivalent to heating ~16,000 and powering ~15,000 homes (US EIA, 2001). Furthermore, the amount of water saved by rbST use is equivalent to the annual amount required to supply ~10,000 homes - a considerable environmental benefit in areas where water consumption is a significant concern. Finally, the carbon footprint of the dairy population supplemented with rbST is reduced by 1.9 billion kg per year; this is equivalent to removing ~400,000 cars from the road or planting ~300 million trees. A population containing one million rbST-supplemented cows is equivalent to ~15% of the current US dairy herd; therefore the potential for widespread rbST use to mitigate the environmental impact of dairy production should not be underestimated.

Productive Efficiency – Future Opportunities

The sustainability of the dairy system will continue to be a significant issue and continued efforts to mitigate the environmental impact of dairy production will be of special importance. It is, therefore, essential for dairy producers to identify opportunities to adapt or adopt management practices that promote environmental stewardship and resource conservation. At present, rbST is the only technology that has the potential to singly reduce total environmental impact by 9%; however, the implementation of strategic environmental planning that includes a variety of mitigation practices allows the producer to make decisions and combine practices according to both environmental and economic indices. Previous studies have evaluated the effects of milking frequency, ration formulation, photoperiod and reproductive management (Bosch et al., 2006, Dunlap et al., 2000, Garnsworthy, 2004, Jonker et al., 2002); while these evaluations provide insight, they focused on single environmental parameters (e.g. N or methane) and did not use the LCA approach. A more complete evaluation of the environmental impact of specific management factors that are under producer control, such as calving interval, age at first calving, use of artificial insemination and milk somatic cell count, is the focus of current investigation by our group.

Under normal market conditions, improving productive efficiency has a tangible economic benefit, but this also raises the question of how producers will assess the commercial value of environmental impact mitigation. Introduction of carbon credits or a cap and trade system would necessitate quantification of the impact of different management practices so to provide compensation for their implementation. Furthermore, discussion would be necessary as to the allocation of carbon credits between the dairy and beef industry, and adjustments made for the carbon credits earned by the dairy industry when by-products from the human food and fiber industries are utilized as feed and converted to high-quality dairy products.

Conclusion

Dairy producers have made vast gains in productive efficiency over the last century and should continue to do so, but only if the technologies and practices that improve productive efficiency continue to be available for use. It is thus essential to educate consumers, retailers, processors and policy-makers of the vital importance of scientific evaluation based on efficacy, human/animal safety and environmental analysis rather than misplaced ideological or anthropomorphic concerns. A scientific evaluation of the environmental component may be achieved through quantifying the impact on a system basis, incorporating the resources required and waste produced from the entire dairy population and expressing results per unit of milk produced. Such evaluation facilitates true consumer choice and avoids perpetration of non-scientific or flawed claims relating to the nutritional or environmental advantages of alternative systems.

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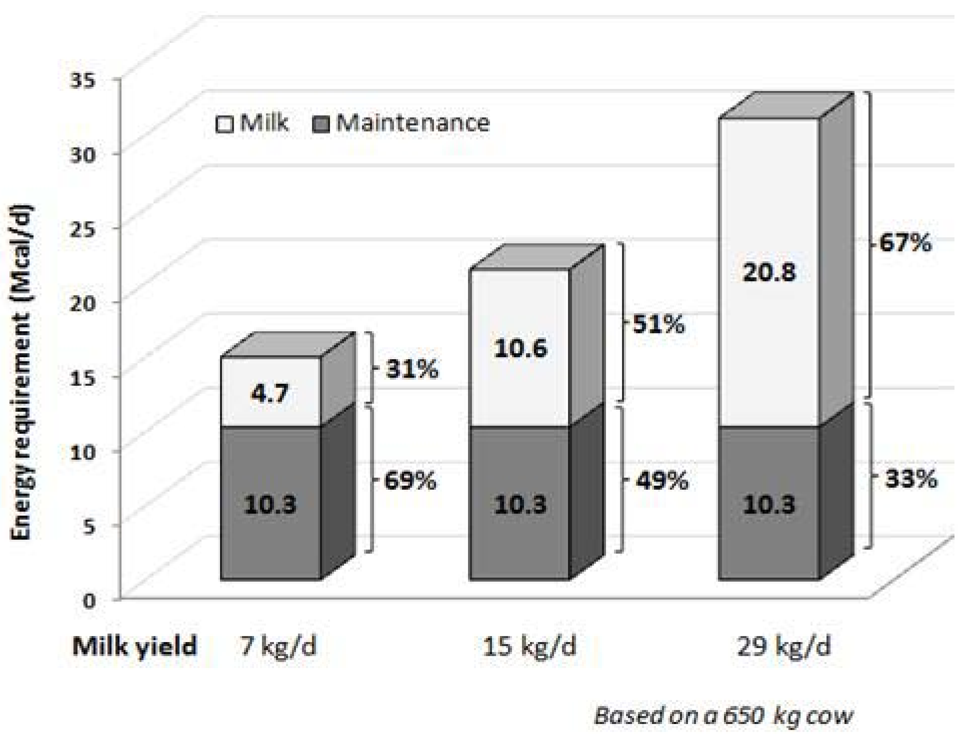

Figure 1. Illustration of productive efficiency and the “dilution of maintenance” effect. Adapted from Capper et al. (2009).

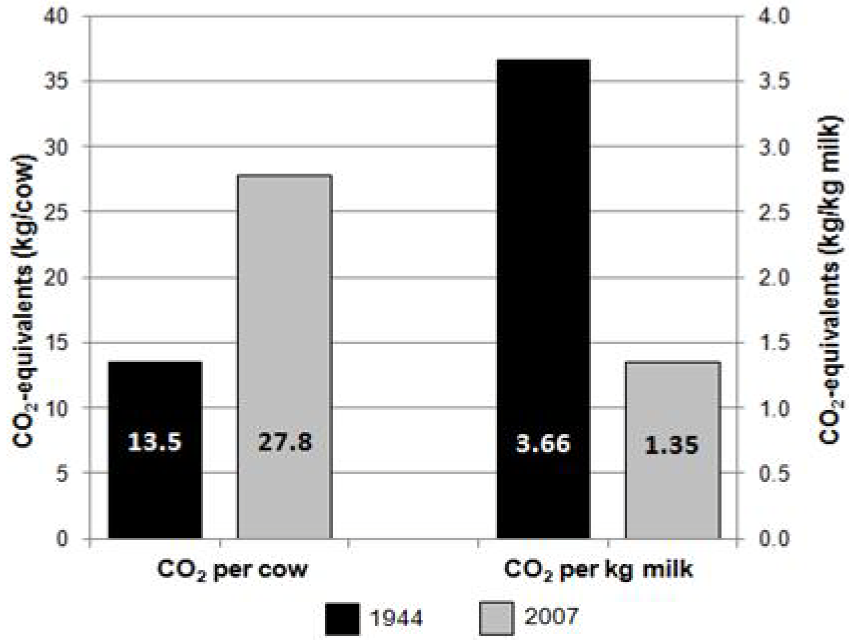

Figure 2. Comparison of the carbon footprint of milk production on a cow basis and on a kg milk basis for the 1944 and 2007 dairy production systems. Adapted from Capper et al. (2009).

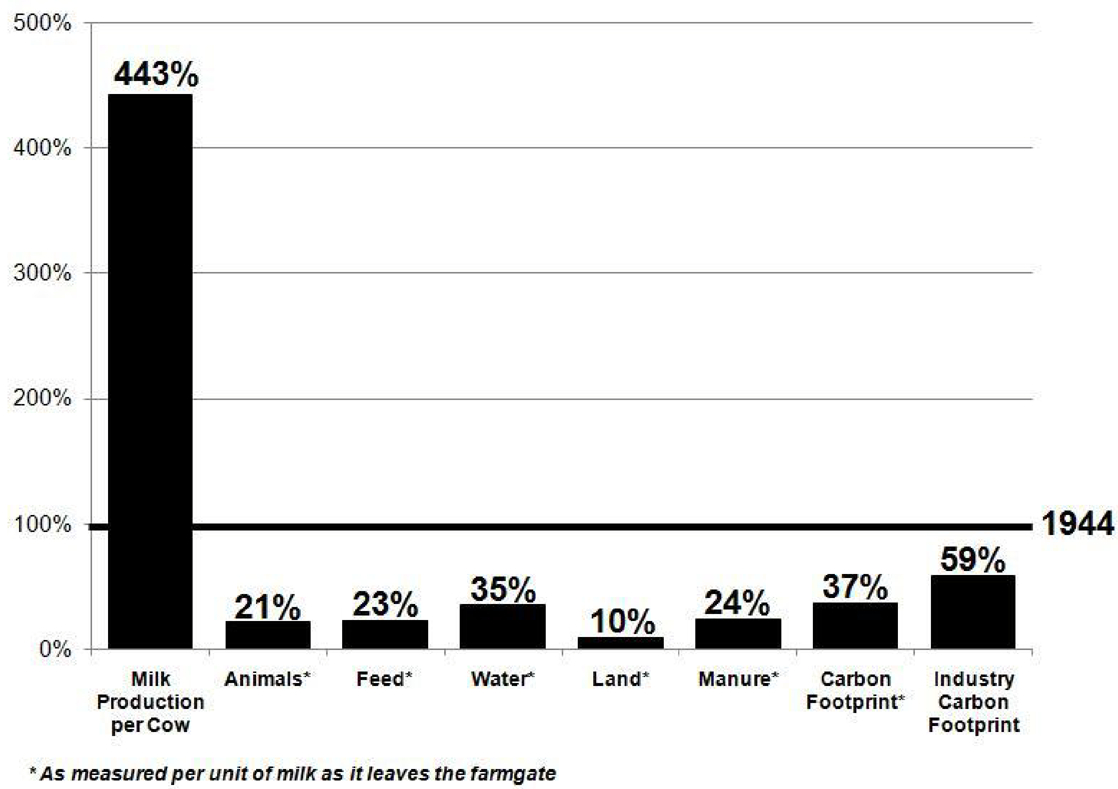

Figure 3. The 2007 U.S. milk production, resource use and emissions expressed as a percentage of the 1944 dairy production system. Adapted from Capper et al. (2009).

Table 1. Annual resource inputs and waste output from a population containing one million rbST-supplemented dairy cows[a] compared to equivalent milk from an unsupplemented population. Adapted from Capper et al. (2008)

	Without rbST	With rbST	Reduction with rbST use
Production Parameters			
Milk production (kg/y x 10^9)	14.1	14.1	
Number of lactating cows (x 10^3)	1,338	1,180	157
Number of dry cows (x 10^3)	217	192	25
Number of heifers (x 10^3)	1,291	1,139	152
Nutrient requirements			
Maintenance energy requirement[b] (MJ/y x 10^9)	54.1	47.8	6.3
Maintenance protein requirement[b] (t/y x 10^3)	667	606	61
Feedstuffs (t freshweight/y x 10^6)	25.9	23.7	2.3
Waste output			
Nitrogen excretion (t/y x 10^3)	100	91	9.6
Phosphorus excretion (t/y x 10^3)	45.7	41.4	4.3
Manure, freshweight (t/y x 10^6)	34.9	32.2	2.8
Gas emissions			
Methane[c] (kg/y x 10^6)	495	454	41
Nitrous oxide (kg/y x 10^3)	100	91	9.6
Total carbon footprint[d] (kg CO_2/y x 10^9)	21.6	19.7	1.9
Cropping inputs			
Cropping land required (ha x 10^3)	2,712	2,493	219
Nitrogen fertilizer (kg/y x 10^6)	101	92	8.6
Fossil fuels[e] (MJ/y x 10^6)	8,840	8,111	729
Resource use			
Electricity (kWh/y x 10^6)	1,350	1,195	156
Water (l/y x 10^9)	66.9	61.5	5.4

[a] One million lactating cows supplemented with rbST plus associated ineligible lactating cows, dry cows and replacement heifers. The average unsupplemented cow had a lactation average milk yield of 28.9 kg/d (NAHMS, 2007) and the milk response to rbST was +4.5 kg/d.
[b] Refers to nutrients required for maintenance (all animals), pregnancy (dry cows) and growth (heifers).
[c] Includes CH_4 from enteric fermentation and manure fermentation.
[d] Includes CO_2 emissions from animals and cropping, plus CO_2 equivalents from CH_4 and N_2O.
[e] Only includes fuel used for cropping.

SESSION NOTES