The Role of Productivity in Improving the Environmental Sustainability of Ruminant Production Systems

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Abstract
The global livestock industry is charged with providing sufficient animal source foods to supply the global population while improving the environmental sustainability of animal production. Improved productivity within dairy and beef systems has demonstrably reduced resource use and greenhouse gas emissions per unit of food over the past century through the dilution of maintenance effect. Further environmental mitigation effects have been gained through the current use of technologies and practices that enhance milk yield or growth in ruminants; however, the social acceptability of continued intensification and use of productivity-enhancing technologies is subject to debate. As the environmental impact of food production continues to be a significant issue for all stakeholders within the field, further research is needed to ensure that comparisons among foods are made based on both environmental impact and nutritive value to truly assess the sustainability of ruminant products.
INTRODUCTION

The global agricultural industry faces a challenge in providing enough safe, affordable, and abundant food to supply the growing population. According to the World Food Summit, “Food security exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life” (1). According to estimates from the Food and Agricultural Organization (FAO) of the United Nations, the global population will reach 9.5 billion people by the year 2050, and food production will need to increase by 70% to provide worldwide food security (2). Food demand for livestock products will not rise in a linear fashion—demand is expected to double in sub-Saharan Africa, South Asia, and other developing regions, which also will see the greatest rise in population numbers, with relatively little change in developed countries (3). Dwindling supplies of nonrenewable resources (e.g., fossil fuels, minerals) exacerbate this challenge, which is complicated further by the burden that an increased population places upon renewable resources such as land and water. Available cropland per person is predicted to decline by 25% between 2010 and 2050 (4); thus, there is a clear need to improve yields per unit area of land as well as total food production. However, a desire to improve agricultural sustainability runs in tandem with the need to produce greater amounts of food per unit area, and these two needs often are considered to conflict.

The Brundtland Report provides what is arguably the most widely used definition of sustainable development, which is that it “meets the needs of the present without compromising the ability of future generations to meet their own needs” (5, p. 5). This can be further dissected into three components: environmental stewardship, economic viability, and social responsibility (6). For a system or industry to be sustainable, all three components must balance—if one factor is misaligned, the system cannot achieve long-term sustainability. Animal welfare considerations on modern dairy farms serve as an example of this balance; optimal animal care represents the producer’s social responsibility and is linked intrinsically to system productivity. If the animal’s well-being and health are compromised, milk production and the efficiency of resource use declines, which thereby has adverse effects on both the economic viability and environmental stewardship of the dairy operation.

The environmental impact of food production has focused, to date, on greenhouse gas (GHG) emissions, also referred to as the carbon footprint. A complete analysis, however, also would need to consider water use as well as land- and air-quality aspects. There is no doubt that GHG emissions are of vital importance, especially in light of food stakeholder concerns relating to climate change, but it should be remembered that water use is likely to be the major limiting factor, and thus a critical environmental metric in the near future. Nevertheless, the science relating to GHG emissions is more developed at present than estimates of water or other resources per unit of food; therefore, GHG emissions can be used as a proxy for environmental impact. Global GHG emissions from all agriculture were estimated by Bellarby et al. (7) to account for between 17% and 32% of all human-induced emissions, and the Environmental Protection Agency (EPA) (8) estimated that agriculture contributes approximately 6% of the total US carbon footprint, with animal agriculture accounting for half of the agricultural component. A recent report by the FAO (9) concluded that animal agriculture was reported to account for 18% of GHG emissions, and these conclusions have been adopted eagerly by activist groups as evidence for the benefits of a vegetarian or vegan lifestyle (10, 11).

The methodology and results of the FAO report have been discussed at length (12, 13). Pitesky et al. (12) credited the FAO report with sound recommendations as to the importance of improving productivity and efficiency to reduce future GHG emissions, but they documented
discrepancies in methodology between analyses of animal agriculture and other sources of GHG emissions that led to the marked overestimation of the global contribution made by animal agriculture. Nonetheless, Pelletier & Tyedmers (14) suggest that animal agriculture accounted for 14% of global GHG emissions in the year 2000, and given that a subsequent FAO report calculated that global dairy production contributes 4% to global anthropogenic GHG emissions (15), it is clear that animal agriculture makes a significant contribution. Given current concern over this issue, and assuming that consumer demand for ruminant animal proteins will remain high, this paper discusses the options available for improving the environmental sustainability of ruminant production.

EVALUATING THE ENVIRONMENTAL SUSTAINABILITY OF RUMINANT PRODUCTION

Choosing an Environmental Sustainability Metric

Ruminant production systems are inherently variable across regions and climates, with considerable diversity conferred by management systems and production practices. For example, the majority of beef production systems in the United States are characterized by an industry comprising seed stock producers, cow-calf operators, backgrounders, and feedlots, with a small quantity of calf inputs from the dairy industry and considerable technological inputs. By contrast, European beef production systems tend to employ less-intensive finishing systems, with a greater reliance on crossbred calves from the dairy industry. To attempt to determine the environmental impact of any one of the myriad individual subsystems that comprise beef production in the United States or Europe would render interregional comparisons meaningless. Yet all of these industries exist to supply animal protein for human consumption, with associated by-products including hides, fertilizers, and pharmaceuticals. Whole-system analyses therefore have evolved to encompass all relevant resource inputs and waste outputs within the defined boundaries of a production system and thus facilitate comparisons between regions and production systems.

Early environmental analyses used limiting resource availability as the denominator, for example using carbon emissions per unit of land to compare the environmental impact of conventional versus organic dairy production (16). However, such denominators again lead to difficulties in regional comparisons and do not consider externalities—it is not obvious whether a unit of land used for dairy production in the Netherlands has food production potential equivalent to that of a unit of land in the Midwestern United States or arid regions of Australia. The accepted functional unit for environmental comparisons among ruminant systems therefore has become the unit of food (kg, t); for ruminant production this translates to mass of milk for dairy or meat for beef and lamb. Given the wide variation in milk composition, as discussed by Bertrand & Barnett (17), this has been further refined to units of fat and protein-corrected (or energy-corrected) milk when assessing dairy production’s environmental impact. This corrects for production-system variation, but it still may lead to confusion when consumers concerned about the environmental impact of their food choices choose foods based on carbon emissions without due regard for differences in nutrient composition.

The Relationship Between Ruminant Productivity and Environmental Impact

Resource use and GHG emissions decline with increased productivity and feed efficiency—ruminant production systems tend to have a greater environmental impact than the vertically integrated, monogastric production systems. Nonetheless, the US dairy and beef industries have
made significant productivity gains over the past century in tandem with increasing intensification of ruminant production systems. The US dairy industry is considered to have originated with the importation of European cattle to the Jamestown settlement in 1611, and the earliest recorded US milk production data relate to a Jersey cow that produced 232 kg of milk in a 350-day lactation in 1854 (18). Annual average milk yield per cow has increased from 1,890 kg in 1924, when USDA dairy production record keeping began, to 9,682 kg in 2011 (19), and the current record-holding cow (named Ever-Green-View My 1326) produced over 32,800 kg.

The introduction of genetic selection tools and the potential to produce a large number of high-genetic merit offspring via artificial insemination have allowed dairy producers to make informed decisions as to selection criteria when breeding replacement cattle. The greatest progress since the early 1980s has been made in yield traits, with genetic improvement accounting for approximately 55% of phenotypic gains (20). However, a negative trade-off also has occurred between milk yield and fertility, with a 6% decline in pregnancy rate since 1980 (equivalent to a 24-d increase in calving interval), of which approximately one-third can be attributed to genetics. VandeHaar & St-Pierre (21) noted that, although improved genetics have played a significant role in these productivity gains, advances in nutrition and management practices have been essential to allow dairy cattle to reach their genetic potential for milk yield. Over the past century, the US dairy industry has shifted from extensive production systems based entirely on forage to intensive systems with diets still founded on forage but formulated with feed components to optimize rumen fermentation and meet the dairy cow’s nutrient requirements. This has allowed the use of a variety of feeds, including by-products from the human food and fiber industry, which has resulted in a total mixed ration approach that improves the efficiency of rumen fermentation and digestibility, more adequately meets the cow’s nutrient requirements, and allows for greater performance (21, 22). In combination with improved knowledge of dairy cattle health and welfare, modern management practices have demonstrably improved productivity within the dairy industry.

Productivity advances also have occurred within the US beef industry, with a regressed annual increase in beef yield per animal of 2.09 kg between 1930 (average yield 239 kg/animal) and 2010 (average yield 350 kg/animal) (19). The US beef industry has followed similar trends in improving productivity to those of the dairy industry; however, owing to regional and climatic variation within cow-calf and backgrounder operations, and to the nutritional, labor, and economic limitations imposed by forage-based diets within these systems, the greatest rate of progress in terms of growth rates, technology adoption, and feed efficiency has been made within finishing operations (23). Until the 1950s, the majority of beef consumed in the United States was produced in pasture-based systems; however, the advent of finishing diets formulated to meet cattle requirements and containing a significant proportion of corn and by-product feeds, with consequent improvements in growth rate, intramuscular fat, and grading score, encouraged producers to move toward a more intensive system (24).

The Dilution of Maintenance Concept

Every animal requires a certain amount of nutrients on a daily basis to support vital functions, health, and minimum activities (the maintenance requirement) plus an additional nutrient requirement to support production, i.e., growth, pregnancy, or lactation. The maintenance requirement is dependent principally upon bodyweight and thus does not change as a function of production (25). As this daily nutrient requirement is applicable to every animal, the maintenance requirement of the livestock population therefore may be considered as a fixed cost of animal production. When applied to the livestock industry, improving productivity of an individual
animal such that a greater quantity of milk, meat, or eggs is produced in a set period of time, the total maintenance cost per unit of food produced is reduced. Thus, the dilution of maintenance concept is central to improvements in economic viability and environmental sustainability. The latter is especially noteworthy because maintenance represents a cost in terms of both resource use (including feed, land, water, and fossil fuels) and waste output (e.g., manure and GHG). An example of the dilution of maintenance concept is illustrated in Figure 1, in which nutrient requirements are compared for cows at two different levels of production. In 1944, when milk yield averaged 7 kg/d, maintenance represented 69% of the metabolizable energy requirement. In contrast, the maintenance requirement was diluted out over more units of production and represented 37% of metabolizable energy for cows averaging 29 kg/d milk in 2007. Improving productivity consequently reduces resource use and waste output per unit of dairy. This relatively simple mechanism has been the foundation for improvements in the environmental sustainability of the US ruminant livestock industries over the past century (26–28).

RUMINANT LIVESTOCK’S ENVIRONMENTAL IMPACT: THE US PERSPECTIVE

Dilution of Maintenance and the Environmental Sustainability of US Dairy Production

Within dairy production, improving milk yield per cow is the most widely understood productivity measure. The environmental impact of increased milk yield may be exemplified by comparing resource use and GHG emissions from US dairy production in 1944 and 2007, as described by Capper et al. (26). In 1944, the average US dairy farm had six cows fed a primarily pasture-based diet with occasional corn or soy supplementation. Neither antibiotics nor artificial hormones were available for animal use, and animal manures provided fertilizer. In contrast to highly mechanized modern dairy systems, 1944 farms averaged only 1.2 tractors—
the majority of agronomical operations were achieved through draft horse work. This historical system, with a national herd comprising 54% small breeds (Jersey, Guernsey, Ayrshire) and 46% large breeds (Holstein, Brown Swiss) and an average milk yield of 2,074 kg/year, is substantially different from modern dairying. As a result of the previously discussed gains in nutrition, genetics, and management, the average dairy cow produced 9,193 kg milk/year in 2007 and the national herd contained more than 90% Holstein cattle. As described previously, increasing milk yield per cow between 1944 and 2007 diluted out the maintenance cost and reduced the energy required per kg of milk from 15.3 MJ to 7.1 MJ (Figure 1). As milk yield increased, fewer lactating cows were required to produce a set amount of milk, and the number of associated support animals (dry cows, replacement heifers, bulls) in the population decreased; thus, the total population maintenance requirement was reduced. The 2007 dairy industry therefore produced 84.2 billion kg of milk with a national herd containing only 9.2 million dairy cattle (and 89.0 billion kg of milk from the same number of cattle in 2011) compared with 53.0 billion kg of milk from 25.6 million head in 1944. In combination with advances in crop productivity over this time period, feed use per unit of milk was reduced by 77%, land use by 90%, water use by 65%, and manure production by 76% (Figure 2). The carbon footprint of a kg of milk in 2007 was 63% lower than that in 1944 (1.35 kg CO₂-eq compared to 3.66 kg CO₂-eq), and the total dairy industry carbon footprint (with the boundary of the farm gate) was reduced by 41%, despite the substantial increase in total milk production (26).

Mature cow bodyweight has increased concurrently with productivity gains over the past century; thus, although the environmental impact of a unit of milk has been reduced, daily resource use and GHG emissions per animal have increased. This may lead to future legislative complications if environmental assessments are based upon the number of livestock units per operation without consideration of productivity. Although the previous historical example demonstrates the environmental advantages of reducing the number of animals required to

![Figure 2](image-url)

**Figure 2**

Resource use and waste outputs from modern US dairy production systems typical of the year 2007, compared with historical US dairying (characteristic of the year 1944). Data adapted from Capper et al. (26). Abbreviations: GHG, greenhouse gas.
produce a set quantity of milk, the population maintenance requirement is determined by the combination of animal numbers and animal bodyweight. In a comparison of the environmental impact of cheese production from Jersey and Holstein milk, Capper & Cady (29) demonstrated that land use, water use, and GHG emissions were reduced by 32%, 11%, and 20% respectively through the use of Jersey cattle. In this instance, the environmental gains were conferred by a combination of factors, primarily an increase in milk fat and protein content combined with decreases in bodyweight and milk yield for Jersey cattle. Nonetheless, when breed-specific traits were examined in isolation, the difference in bodyweight between Jersey (454 kg) and Holstein (680 kg) cattle led to a 74% reduction in population body mass despite a 9% increase in the total number of cattle required to produce an equivalent amount of cheese. Capper & Cady (29) found that bodyweight was the most influential factor affecting environmental impact, with milk composition (and thus cheese yield per unit of milk) and milk yield following closely behind but with little effect of age at first calving, culling rate, or calving interval. These results were echoed by Bell et al. (30), who reported that changing energy-corrected milk (ECM) yield by one standard deviation conferred a 14.1% decrease in the carbon footprint per unit of ECM compared with feed efficiency, calving interval, or culling rate (6.0%, 0.40%, and 0.14% decreases, respectively).

Improving management practices that have a positive effect on dairy cow productivity, for example reducing calf mortality, improving heifer growth, or decreasing the incidence of mastitis, also will reduce the environmental impact of dairy production. Garnsworthy (31) reported that methane emissions could be reduced by up to 24% by improving fertility within the UK dairy herd and thus reducing the number of heifers required to maintain milk production. Sexed semen also has been suggested as a mechanism to improve productivity by ensuring that heifers are born to superior animals, which thus improves the potential genetic merit and productivity of the herd (32). Nonetheless, if Y-sorted semen were not equally available, this potentially would affect the efficiency of beef production if a greater number of dairy heifer calves were diverted into beef production. Further research is required on the comparative and interactive effects of herd productivity metrics to identify the management practices that have the greatest impact on environmental metrics within systems.

Between-system comparisons of US dairy production’s resource use and GHG emissions again demonstrate the importance of improved productivity. A recent study from the Organic Center (33) concluded that organic dairy production had considerable environmental advantages over conventional systems but made the assumption that productivity was equivalent in both systems. Consumers appear to consider that organic production systems have a lesser environmental impact than their conventional counterparts (34), but the majority of studies comparing yields in organic and conventional production reveal that yields are substantially lower in organic systems both in the United States (35–37) and overseas (16, 38). The nutrient costs for maintenance in an organic system are approximately 20% greater owing to increased nutrients required to support the physical act of grazing (25), and milk yield averages 20% less across studies (39). When the increased nutrient use for maintenance and milk-yield reductions are included in the analysis, the increase in GHG emissions per unit of milk conferred by organic production is approximately 13% (39).

Dilution of Maintenance and the Environmental Sustainability of US Beef Production

In contrast to dairy production, in which lactation length has a relatively narrow range (generally ~300–420 days) and thus the primary dilution of maintenance effect is conferred during lactation,
both beef yield and growth rate have a significant effect upon the environmental impact of beef production. If we compare productivity gains made in conventional beef production systems between 1977 and 2007, average slaughter weight increased over this time period from 274 kg to 351 kg, thus reducing the number of slaughter animals and the size of the national herd required to meet beef meat demand (27). Average growth rate was increased from 0.71 kg/d to 1.16 kg/d between 1977 and 2007, which reduced both the proportion of total energy use apportioned to maintenance from 53% (1977) to 45% (2007; Figure 3) and the average number of days required to reach slaughter weight from 609 to 485. As shown in Figure 4, the reduction in total maintenance requirements conferred by the combination of the reduced beef population and the lesser number of days for animals to reach slaughter weight reduced feed use by 19%, land use by 33%, water use by 12%, fossil fuel use by 9%, and the carbon footprint per kg of beef by 16% (27).

Yield gains within the US beef industry have been significant over the past century, but anecdotal evidence from the processing and retail industry suggests that slaughter weights have reached a plateau. Consumer demand for portion sizes greater than those conferred by the current average slaughter weight of 582 kg (40) is unlikely to increase, and the current processing infrastructure is ill-equipped to deal with larger carcass sizes without considerable reorganization. This is unfortunate, because the negative correlation between beef yield and population size required to maintain beef production means that yield gains have a substantial effect on total environmental impact, particularly as the supporting population (i.e., cow-calf herd) contributes the greatest proportion of GHG emissions per unit of beef (41) and is less susceptible to dietary modification of enteric methane emissions than cattle in other sectors owing to their forage-based diets (42). Within an efficient cow-calf system, calves should be weaned at approximately half the dam’s mature weight, but given the nutritional limitations of pasture-based diets, this is difficult to

![Figure 3](image-url)

The impact of the increasing growth rate of beef cattle on the proportion of daily energy used for maintenance versus growth in 1977 compared with 2007—the dilution of maintenance effect. Data adapted from Capper (27). Abbreviations: ME, metabolizable energy; MJ, megajoules.
achieve when mature cows approach or exceed 635 kg bodyweight. Although Notter et al. (43) reported some advantages of increased mature weight upon cow-calf system efficiency, if calf growth rates and weaning weights can be maintained from cattle with a mature weight of less than 580 kg, environmental sustainability will be improved. Furthermore, according to US Department of Agriculture data (44), only 89.1% of cattle produce a live calf each year in US systems; if this were increased substantially, the consequent reduction in population size required to support beef production would be expected to have a considerable effect upon beef’s environmental impact.

Conventional production systems contribute approximately 97% of total US domestic beef supply and are characterized by forage-based cow-calf and backgrounder operations followed by an intensive finishing period on corn-based diets (45). Given the reliance of these systems on fossil fuel and fertilizer inputs for feed production and transportation, they may appear to have an intrinsically greater environmental impact than pasture-based systems. Indeed, Sithyphone et al. (46) conclude that increased GHG emissions per animal confer an environmental disadvantage for corn-finished beef cattle compared with their hay-fed compatriots in Japanese systems. However, as discussed previously, assessing environmental impact on a per-head basis fails to account for the productivity of the system; in this instance, the slaughter weight of corn-fed cattle was almost double that of hay-fed cattle, which would have a considerable effect upon GHG emissions per unit of beef.

Both Capper (45) and Pelletier et al. (41) reported that GHG emissions per unit of beef meat were greater in pasture-finished systems than in feedlot systems. Pelletier et al. (41) cite GHG emissions of 19.2 kg CO₂-eq/kg liveweight for pasture-finished beef compared with 16.2 kg CO₂-eq/kg liveweight for yearling-fed beef, whereas Capper (45) reports 26.8 kg CO₂-eq/kg hot carcass weight beef for pasture-finished beef and 16.0 kg CO₂-eq/kg hot carcass weight beef for feedlot beef. In both studies, the increased GHG emissions associated with pasture-finished beef were a direct consequence of slower growth rates and lower slaughter weights. Pelletier et al. (41) further showed that calf-fed beef, i.e., a system in which calves bypass the backgrounder stage and enter

![Figure 4](image-url)

**Figure 4**
Comparative resource use and waste outputs per unit of beef produced in US systems characteristic of 1977 compared with 2007. Data adapted from Capper (27). Abbreviations: GHG, greenhouse gas.
the feedlot directly as weaned calves, had the lowest GHG emissions (14.8 CO₂-eq/kg liveweight beef) as a consequence of an increased growth rate and thus fewer days to reach slaughter weight compared with yearling-fed cattle. Although pasture-based beef production systems predominated in the first half of the twentieth century within the United States, the increased land required to supply sufficient beef meat for the current domestic and international market would render whole-scale conversion of the US beef production system to pasture-fed production practically impossible. However, if conversion did occur and annual beef production was maintained at 11.8 billion kg (40), the increase in carbon emissions would be equal to adding 25.2 million cars to the road on an annual basis (45).

Pasture-based beef finishing systems have the potential to reduce net GHG emissions through carbon sequestration. Pasture does not, however, sequester carbon indefinitely, nor does sequestration occur at a constant rate (47, 48). Over time, soil carbon concentrations reach an equilibrium beyond which no further sequestration occurs unless land is subjected to significant management change (47, 48). The present body of literature indicates that the degree to which carbon may be sequestered by crop- or pastureland is infinitely variable among systems and is dependent on a multitude of factors including land-use change, tillage, organic matter input, soil type, and crop or pasture species (49, 50). Reliable data on carbon sequestration under a range of environmental conditions and global regions are notably lacking from environmental literature, and this is one area where future research would pay dividends in bridging the current knowledge gap.

The reliance of both conventional and pasture-based US beef systems upon pasture- and forage-based diets for animals within the cow-calf and backgrounder systems means that any potential mitigating effect of carbon sequestration could be attributed only to differences in the finishing period. Pelletier et al. (41) calculated that sequestration at a rate of 0.4 tons C/ha/year would reduce the GHG emissions from pasture-based beef production to 11.2 kg CO₂-eq/kg liveweight. However, when differences in dressing percentage and thus beef yield per animal between pasture-finished and feedlot beef are considered, this would underestimate GHG emissions per unit of beef produced. Owing to greater GHG emissions from pasture-finished beef cattle in the study by Capper (45), sequestration would need to exceed 1.3 tons C/ha/year to produce pasture-finished beef with GHG emissions similar to feedlot beef. Either estimate is a lofty target, given that Bruce et al. (51) suggest that the potential for carbon sequestration in well-managed pastureland is 200 kg/ha, whereas Conant et al. (52) estimate the potential for sequestration at 540 kg/ha. Furthermore, complete comparisons of environmental effects need to be based on an equivalent production of meat and account for the increased requirement for land and feed, the greater supporting herd population (cows, calves, heifers, and bulls) conferred by slower growth rates and reduced slaughter weights in the pasture-finished system, and the propensity for pasture-based diets to increase ruminal methanogenesis and thus enteric GHG emissions (53, 54). However, this is still complicated by the fact that approximately 24% of beef production results from dairy systems in the United States (either through the provision of cull cows or dairy calves raised for beef), thus a whole-system large ruminant analysis may be required to properly assess the environmental impact of beef and dairy production in future.

**Ruminant Livestock’s Environmental Impact: The Global Perspective**

Worldwide, ruminant livestock make a significant contribution to sustainability through provision of nutrition via animal-source foods in combination with fertilizer, draft power, social standing, and economic income (3, 55, 56). Animal system productivity within developing regions
generally is diminished owing to a combination of factors including inadequate nutrition (as a consequence of both feed quality and quantity and lack of nutritionally balanced diets), lack of access to genetic selection techniques, and increased incidence of livestock disease (3). With reference to animal health, developed nations have seen a reduction in the burden placed by animal disease as a result of improved veterinary services and vaccine availability and the implementation of preventative medicine programs (57), although concern is rising with regard to the emergence and spread of new diseases such as avian influenza H5N1 and the Schmallenberg virus (58). Nonetheless, relatively little progress has been made in the developing world save for the eradication of rinderpest (59). The World Organization for Animal Health estimates that worldwide, more than 20% of animal protein is lost as a result of disease (60); thus, significant potential exists to reduce the environmental impact of global livestock production through improving health.

Global livestock production has increased substantially over the past 50 years—beef production has doubled, poultry meat production has increased almost tenfold, and both dairy and egg yields have increased by approximately 30% (61). Major international dairy regions (including the United States, Canada, New Zealand, and Europe) all have improved milk yield per cow since the 1960s, the rate of improvement varying from 129 kg/year and 117 kg/year for the United States and Canada, respectively, to 77 kg/year and 24 kg/year for Europe and New Zealand (61, 62). A portion of the variation in the rate of improvement may be related to genetic selection priorities, for example the need for smaller-framed, lower-yielding cattle in antipodean systems compared with the trend for increasing yields in the United States and Canada (63). Nevertheless, the environmental effects of regional productivity variation are exemplified by the results of a recent FAO (15) report that modeled GHG emissions from dairy production using life-cycle analysis. As intensity of production declines and the average milk yield shifts from approximately 9,000 kg/cow for North America to ~250 kg/cow for sub-Saharan Africa, the carbon footprint increases from 1.3 kg CO$_2$-eq/kg milk to 7.6 kg CO$_2$-eq/kg milk (Figure 5). If environmental sustainability were the only consideration, the FAO data could provoke the conclusion that all regions should adopt North American– and Western European–style

![Figure 5](http://www.annualreviews.org/doi/abs/10.1146/annurev-animbio-042812-135008)

Figure 5
Average annual milk yield and carbon footprint per unit of energy-corrected milk across global regions. Data adapted from Food Agric. Organ. (15).
production systems, or that dairying should be focused in these areas and discouraged in less-productive regions such as sub-Saharan Africa and South Asia. However, the significant social (both status and nutritional) and economic value of dairying in less-developed regions must not be underestimated. The challenge for global dairy production is to improve productivity and optimize sustainability within each region rather than prescribe one-size-fits-all production systems or management practices.

At present, no comprehensive analyses have compared the environmental impact of beef production across global regions. A literature scan reveals a range of GHG emissions attributed to beef production from 9.90 kg CO2-eq/kg carcass weight for intensive production in Australia (64) to 44.0 kg CO2-eq/kg carcass weight for Brazilian production with land-use change and deforestation taken into account (65). Biologically, the dilution of maintenance concept would suggest that improving productivity through intensification (as discussed previously with reference to US systems) should reduce environmental impact on a global basis, but a pasture-based Australian system (64) is cited as having GHG emissions per unit of beef considerably lower than those exhibited by a range of intensive systems (41, 45, 66–69). In this instance, a considerable amount of the variation in GHG emissions may simply be attributed to differences in methodology and system boundaries. For example, Ogino et al. (67) examined the environmental impact of the finishing system alone; Pelletier et al. (41) assumed that identical cow-calf systems were used to supply calves to both calf-fed, yearling-fed, and pasture-based finishing systems; and Capper (45) included the effect of production-enhancing technology in the analysis. As discussed by Bertrand & Barnett (70) with reference to dairy production, a definitive methodology for comparing the environmental impacts of beef production systems will be required in future.

**FUTURE ON-FARM STRATEGIES TO ENHANCE SUSTAINABILITY OF RUMINANT PRODUCTION**

Future gains in environmental sustainability can be achieved only through continuous improvement within all sectors of ruminant production, with specific emphasis placed on improving productivity. Identifying the best management practices that can be applied throughout the national and global industries, without bias toward specific systems, will be key in encouraging producers to maximize efficiency and thus reduce environmental impact and improve economic viability. The use of production-enhancing technologies (PET) provides a clear opportunity to improve environmental sustainability. Examples include technologies that alter nutrient partitioning toward milk production (lactating animals) or lean muscle accretion (during growth), improve feed quality, enhance rumen fermentation and diet digestibility, increase reproductive performance, improve herd health programs, and promote animal welfare (28, 39). However, a dichotomy often exists between consumers’ desire for environmentally sustainable foods (71) and a mistrust of technology use within food production (3).

Recombinant bovine somatotropin (rbST) provides an example of PET use within dairy production. This technology alters nutrient partitioning, which results in an increase in daily milk yield of an average of 4.5 kg per cow (39, 72). This increase affects environmental sustainability through the dilution of maintenance concept, the net effect being that rbST use reduces the amount of land required to produce a unit of milk by 9.2%, water use by 10.4%, and the carbon footprint by 9.1% (39). On an industry basis, rbST supplementation of 1 million cows would therefore reduce the dairy industry’s carbon footprint by the annual equivalent of removing ~400,000 cars from the road. The mitigating effect of rbST use on environmental impact has also been noted by other investigators (72–77), including Johnson et al. (78), who
suggested that large-scale use of rbST would reduce methane emissions by approximately 9%. Nonetheless, the political and social acceptability of rbST use within dairy production has been a contentious issue in several countries (79–81).

As discussed previously, opportunities to improve beef system productivity through greater slaughter weights are limited; however, considerable potential exists to further improve efficiency through improving growth rate, which thereby improves environmental sustainability (27, 45, 82). Technologies such as hormone implants, ionophores, and beta-agonists may be used effectively to improve growth rate, but these may be perceived as undesirable by the consumer owing to concerns relating to animal welfare (83, 84), human health (85), or environmental impact (86). Nonetheless, perceived concerns may not follow through into consumer purchasing behavior. Lusk et al. (87) demonstrated no difference in consumer valuation of beef from hormone-treated or nontreated animals in the United States, Germany, and the United Kingdom; however, such concerns are cited often by processors and retailers as rationales for prohibiting PET use within the supply chain. Capper & Hayes (88) demonstrated that, through an increase in production costs, the global competitiveness of US beef would be reduced by whole-scale PET removal, which would increase resource use on an annual basis and cumulatively increase global GHG emissions through a deficit in US beef production being compensated for by increased production in less-efficient regions.

Technological approaches to directly reduce GHG emissions from ruminants include the inclusion of tannins in the diet to reduce the release of N₂O from manure (89), nitrification inhibitors to reduce N losses from pastureland (90), and use of various approaches to reduce rumen methane production (91). Within the latter category, methane is of particular interest because, depending on diet, ruminants lose 2–12% of digestible energy intake as methane (54). On a global basis, this represents ~28% of methane production (92). Methane is a normal product of ruminal fermentation, representing a pathway for the disposal of metabolic hydrogen produced during microbial metabolism. Therefore, strategies to reduce ruminal methane production center on reducing the population of microbes involved in methanogenesis or providing alternative sinks for metabolic hydrogen. These approaches include use of high-grain diets, addition of lipid supplements, chemical antimicrobials (e.g., bromoethanesulfonic acid), ionophores (e.g., monensin), and immunization against rumen methanogens (91–94). Most of the technologies for enteric methane abatement have shown somewhat inconsistent results. Although methane production can be mitigated for short periods, the dynamic nature of the rumen ecology allows for adaptation as the microbial population reverts to the initial fermentation pattern (93). Furthermore, mitigation strategies often affect more than just methanogenesis such that rumen fermentation rates, digestibility, and intake are reduced, which thereby adversely affects animal performance (94, 95). Further scientific advances are inevitable within this field, but at present, productivity advances appear to confer a greater environmental (and economic) gain than specific technologies that target GHG emissions.

COMPARISON OF ANIMAL SOURCE FOODS WITH PLANT SOURCE FOODS

Human diet quality is assessed by the extent to which it provides the entire complement of high-quality protein, energy, minerals, trace metals, and vitamins necessary to meet human requirements. Consuming a high-quality diet is important for everyone, but children, pregnant and lactating women, and the elderly are most vulnerable to nutritional inadequacies. The value of dairy products and beef meat (referred to as animal source foods) in meeting the food security and nutritional needs of the global population is well recognized (96–98), and they are included in dietary recommendations to promote human health and well-being by
governments and public health organizations around the world. Dairy products and meat are nutrient-dense foods that represent the predominant, most affordable source for many essential dietary nutrients (99–102). Multidisciplinary studies in developing countries have established that schoolchildren consuming diets with little or no animal source foods have an inadequate intake of essential micronutrients that results in negative health outcomes including poor growth, suboptimal cognitive performance, neuromuscular deficits, psychiatric disorders, and mortality (96, 97). Meta-analyses of prospective cohort studies with disease events and death as the outcomes also provide convincing evidence that consumption of milk and dairy products is associated with survival benefits in long-term health maintenance and with the prevention of chronic diseases including diabetes, cardiovascular disease, and many types of cancer (103–105).

The environmental sustainability of animal agriculture systems is currently under scrutiny by both impartial scientific associations (9) and agenda-driven activist groups (11, 106). The consensus opinion is that animal agriculture uses a significant amount of resources and makes a significant contribution to global carbon emissions (9, 14). The majority of food-related GHG emissions are generated during farming; thus, there has been interest in using whole-system approaches to compare the environmental impact of animal source foods in comparison with plant source foods. The purpose of food consumption is to supply nutrients within a balanced diet that sustains development, health, and well-being throughout the life cycle. Unfortunately, comparisons of the environmental sustainability among foods have not used a metric that is functional from an environmental perspective while recognizing the nutrient value of different foods. For example, studies comparing animal and plant food sources on the basis of GHG emissions per unit of mass or food energy (107–111) uniformly concluded that producing plant source foods, such as cereal grains, rather than animal source foods minimized the carbon footprint. Similar conclusions were reached by investigators evaluating GHG emissions per unit of selected macronutrients (e.g., protein) who concluded that the environmental impact of food production could be mitigated by replacing dairy products and meat with plant source foods (109, 112–115). However, the latter comparisons did not recognize that animal source proteins have a high digestibility and a near-ideal balance of essential amino acids, whereas plant proteins have a lower bioavailability and are typically deficient in one or more essential amino acids (97, 116). Given that food sources also differ in their composition of other essential macro- and micronutrients, it is critical that these also be considered in comparisons of the environmental sustainability of alternative food choices.

Nutrient density index, also referred to as nutrient profiling, is a system that allows comparison of foods based on their full nutrient content (117, 118). Smedman et al. (119) were the first to use a nutrient density index in comparisons of the environmental sustainability of different food sources. They compared the provision of required nutrients (nutrient density, ND) in relation to GHG emissions (climate index, CI) for a variety of beverages, expressed as an index of the two metrics. As shown in Figure 6, milk had a substantially more favorable NDCI index than other beverages, including orange juice, soy drink, and oat drink. Animal source foods not only supply high-quality and readily digested protein and energy but are also a compact and efficient source of readily available micronutrients. Clearly future considerations of the environmental sustainability of food sources needs to utilize an approach similar to that of Smedman et al. (119) so that the evaluations include a functional metric that is relevant from both a nutritional and an environmental perspective.

The suggestion that animal agriculture should be abolished and that the global population could subsist upon a vegetarian or vegan diet (11, 112, 120) is somewhat myopic. Most comparisons are based on substituting plant source foods for animal source foods on the basis of mass...
or energy (calories), and these results are extrapolated to estimates of impact on GHG emissions. For example, the Environmental Working Group (11) ignored nutritional needs and published a report suggesting that whole-scale adoption of a vegetarian or vegan diet by the US population would reduce national GHG emissions by 4.5% annually, but the US EPA (8) allocates only 3.1% of total GHG to animal agriculture (including all food animals and equines). Less-extreme reductions in consumption of animal source foods often are proposed as a solution to reducing anthropogenic carbon emissions, although Millward & Garnett (121) note that this poses significant nutritional challenges and would result in increased fortification of foods to provide essential nutrients. Nonetheless, the so-called Meatless Mondays campaign was invigorated by Weber & Matthews (111), who considered only the calories available from differing food choices and concluded that changing from red meat and dairy to fish, chicken, or vegetable sources for one day per week’s worth of calories would mitigate GHG to a greater extent than buying all locally sourced food. However, a simple calculation based on US EPA data for the contribution of red meat and dairy to national GHG emissions (3.05% in total) demonstrates that if the entire US population removed these food sources from their diet for one day per week, it would reduce GHG emissions by a maximum of 0.44%, without accounting for adequacy of meeting nutritional requirements or the increased production of alternative food sources. Any attempt to reduce anthropogenic GHG emissions is laudable; however, it appears that far greater mitigation may be achieved through changes in other societal and industrial activities than simply by reducing meat consumption.

Finally, the use of by-products from human feed and fiber production as animal feeds must be considered as part of any evaluation of the environmental sustainability of animal source foods (Table 1). Activist groups often cite ruminant production systems as being particularly inefficient, as the grains fed to livestock could instead be used to fulfill human energy requirements. However, these claims are based on the assumption that all livestock feeds are human edible, whereas Wilkinson (122) demonstrates that a considerable proportion of livestock feeds are
human inedible; thus, the ratio of human-edible energy or protein inputs into animal production systems compared with human-edible energy or protein output in animal source foods is more favorable than the traditional measures of feed efficiency would suggest. Furthermore, data from the USDA’s Economic Research Service (123) indicate that only 8% of US grazed land is sufficiently productive to be classified as cropland pasture and therefore cannot be used for human food production aside from conversion into animal source foods via grazing. As noted by Kock & Algeo (23) with reference to beef production, the entire ruminant industry must utilize its competitive advantage of forage crops and by-product feeds in an arena where competition between human food and livestock feed is ever increasing.

**CONCLUSIONS AND FUTURE DIRECTIONS**

The importance of productivity gains as mechanisms to improve the environmental sustainability of ruminant production systems is without question. Advances in genetics, nutrition, management, preventative medicine, and animal welfare have improved milk yields in dairy cattle and both slaughter weights and growth rates in beef animals, which has led to reductions in resource use and GHG emissions per unit of animal source foods. Animal source foods are a principal source of essential nutrients, and continuous improvement in all sectors of dairy and beef production will be of crucial importance in future food production systems to meet the dual challenge of producing sufficient animal source foods to supply the growing population while reducing environmental impact. Current research has focused on principal productivity metrics, i.e., milk or meat yields, over time, but a considerable knowledge gap exists as to the contribution made by other on-farm practices and herd dynamics, e.g., the specific effects of improved health, reproduction, or animal bodyweight upon environmental impact. These knowledge gaps must be filled for producers to make future management decisions based on economic viability and environmental sustainability. All stakeholders within food production need to gain a greater awareness of the multifaceted nature of sustainability to make informed production-system and dietary choices in future. This will involve assessing food products through a combination of environmental, nutritional, and economic metrics and will offer conventional livestock producers the opportunity to reclaim the concept of sustainable food production, which is perceived currently as applying only to niche production systems.

**DISCLOSURE STATEMENT**

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.
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