The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production

Judith L. Capper*, Euridice Castañeda-Gutiérrez*[†], Roger A. Cady[‡], and Dale E. Bauman*[§]

*Department of Animal Science, Cornell University, Ithaca, NY 14853-4801; and [‡]Monsanto Company Animal Agricultural Group, 800 North Lindbergh Boulevard, St. Louis, MO 63167-0001

Edited by David H. Baker, University of Illinois at Urbana–Champaign, Urbana, IL, and approved May 2, 2008 (received for review March 12, 2008)

The environmental impact of using recombinant bovine somatotropin (rbST) in dairy production was examined on an individual cow, industry-scale adoption, and overall production system basis. An average 2006 U.S. milk yield of 28.9 kg per day was used, with a daily response to rbST supplementation of 4.5 kg per cow. Rations were formulated and both resource inputs (feedstuffs, fertilizers, and fuels) and waste outputs (nutrient excretion and greenhouse gas emissions) calculated. The wider environmental impact of production systems was assessed via acidification (AP), eutrophication (EP), and global warming (GWP) potentials. From a producer perspective, rbST supplementation improved individual cow production, with reductions in nutrient input and waste output per unit of milk produced. From an industry perspective, supplementing one million cows with rbST reduced feedstuff and water use, cropland area, N and P excretion, greenhouse gas emissions, and fossil fuel use compared with an equivalent milk production from unsupplemented cows. Meeting future U.S. milk requirements from cows supplemented with rbST conferred the lowest AP, EP, and GWP, with intermediate values for conventional management and the highest environmental impact resulting from organic production. Overall, rbST appears to represent a valuable management tool for use in dairy production to improve productive efficiency and to have less negative effects on the environment than conventional dairying.

carbon footprint | environment | greenhouse gas | sustainability | productive efficiency

The global population is projected to increase to nine billion people, reaching stabilization in 2040–2050 (1). The food supply required to meet nutritional requirements in the first half of the 21st century is therefore approximately equal to the total amount of food produced throughout the history of humankind (2). Animal agriculture is an integral component of global food production, and dairy products represent invaluable nutrient sources (3). Remarkable improvements have occurred in milk production over the last century; nevertheless, further production increases will be essential to meet future food requirements (4, 5).

In November 1993, recombinant bovine somatotropin (rbST) was among the first agricultural biotechnology products to be approved by the U.S. Food and Drug Administration (FDA). Somatotropin is a key homeorhetic control in the regulation of nutrient partitioning; its administration to dairy cows increases milk production and improves the efficiency of milk synthesis (6). The biological effects of rbST have been extensively investigated, and the ability of this technology to enhance productive efficiency while maintaining the health and well-being of dairy cows is well established (6, 7). When introducing new agricultural technologies, it is vital to balance their potential environmental impact against benefits in terms of efficiency gains. Two preliminary evaluations based on an estimated milk production response for rbST were published before FDA approval (2, 8).

Improving productive efficiency, defined as milk output per feed resource input, is a critical factor in reducing the environmental impact and natural resource utilization by the dairy industry. Our overall objective was to examine the environmental impact of rbST utilization in lactating dairy cows. To quantify the impact of rbST utilization on environmental resources, we used three approaches. The first model examined the impact of increased productive efficiency for an average U.S. dairy cow when a producer utilizes rbST as a management tool. The second model measured the overall environmental impact of an industry-scale adoption of rbST, assuming one million cows were receiving rbST, compared with a similar quantity of milk produced by a cow population where no rbST was used. The third model examined the environmental impact of achieving future increases in milk supply required to meet recently published U. S. Dietary Guideline recommendations (3) using conventional, conventional with rbST, or organic production systems.

Results and Discussion

Over the last century, advances in the genetics, nutrition and management of U.S. dairy cows have resulted in a >4-fold increase in milk production per cow and a 3-fold improvement in productive efficiency (9, 10). This gain in efficiency, referred to as "dilution of maintenance," has been achieved by the cow's greater use of dietary nutrients for milk synthesis and is the basis for historical improvements in productive efficiency (7, 9).

Dilution of maintenance is also the mechanism behind gains in efficiency when rbST is used. As proof of concept, rbST use reduces the maintenance energy and protein requirements per unit of milk by 11.8% and 7.5%, respectively, and total feed requirements by 8.1% (Table 1). Diets were formulated from major components used in dairy cow rations (11), although in practice, dietary ingredients vary according to the formulation of least-cost rations and include by-products from human food and fiber industries (12).

Waste output is a corollary of energy intake and production level, with excess nutrients and metabolites being excreted (12, 13). Per unit of milk, the dilution of maintenance conferred by the use of rbST resulted in a reduction in manure production by 6.8% and CH_4 output by 7.3% (Table 1). Furthermore, N and P excretion, two major environmental pollutants arising from animal agriculture, were reduced by 9.1% and 11.8%, respectively. Similar reductions in nutrient flows resulting from rbST use were reported for specific geographic locations in studies by

---

Author contributions: J.L.C., E.C.-G., R.A.C., and D.E.B. designed research; J.L.C., E.C.-G., R.A.C., and D.E.B. performed research; J.L.C., E.C.-G., R.A.C., and D.E.B. contributed new reagents/analytic tools; J.L.C., E.C.-G., R.A.C., and D.E.B. analyzed data; and J.L.C., E.C.-G., R.A.C., and D.E.B. wrote the paper.

Conflict of interest statement: R.A.C. is a full-time employee of Monsanto, holding the position of Technical Project Manager for POSILAC rbST with the primary responsibility of ensuring the scientific integrity of Monsanto publications about POSILAC; he also owns Monsanto stock. D.E.B. consults for Monsanto in areas outside the environmental impact area and owns no Monsanto stock. J.L.C. and E.C.-G. have no conflict of interest.

This article is a PNAS Direct Submission.

[†] Present address: Nestlé Research Center, Ver-Chez-les-Blanc Case Postale 44, 1000 Lausanne 26, Switzerland.

[§] To whom correspondence should be addressed. E-mail: deb6@cornell.edu.

www.pnas.org/cgi/doi/10.1073/pnas.0802446105

Table 1. Effects of rbST use on resource input and waste output (per unit of milk) over the lactation cycle of an average cow

	Resource input or waste output per kilogram of milk[*]	Change per unit of milk with rbST use[†], %
Resource inputs		
Net energy for maintenance, MJ	1.73	−11.8
Metabolizable protein for maintenance, g	30.4	−7.5
Total net energy requirement[‡], MJ	4.79	−4.5
Total metabolizable protein requirement[‡], g	77.6	−3.2
Feedstuffs per kg dry matter	0.82	−8.1
Waste outputs		
Methane, g	26.2	−7.3
Manure, kilogram freshweight	1.92	−6.8
N excretion, g	5.67	−9.1
P excretion, g	2.98	−11.8

[*] Based on the average annual milk yield (28.9 kg/d) for 2006.

[†] Use of rbST significantly increases milk production (7); yield response to supplementation equaled 4.5 kg per day.

[‡] Comprises nutrients required for maintenance plus lactation.

Jonker *et al.* (Chesapeake Bay drainage basin; ref. 14), Dunlap *et al.* (Lancaster County; ref. 15), and Bosch *et al.* (Muddy Bay creek watershed; ref. 16).

Gains in productive efficiency offer the producer an opportunity to improve milk production and maintain market supply of milk and dairy products from a smaller dairy population. The second model aimed to provide a U.S. industry perspective by evaluating the environmental impact of supplementing one million dairy cows with rbST compared with the same quantity of milk produced by unsupplemented cows. This industry-scale application would represent ≈15% of cows in the current national herd.

Use of rbST reduces the number of lactating cows required to produce a given quantity of milk by 157×10^3 animals, and also decreases the numbers of associated dry cows and replacement heifers (Table 2). As a consequence, rbST use decreases the total quantities of energy and protein required to maintain the population by 6.3×10^9 MJ metabolizable energy and 61×10^3 metric tonnes (t) of crude protein, respectively. To put these numbers into the context of commonly used feed sources for energy (corn) and protein (soybeans), the nutrient savings are equivalent to 491×10^3 t corn (metabolizable energy = 12.9 MJ/kg) and 158×10^3 t of soybeans (48% crude protein). Supplementing one million lactating cows with rbST also reduces total feedstuff use by 2.3×10^6 t per year, with a parallel reduction in cropland of 219×10^3 ha (Table 2). Cultivation of agricultural land is associated with destabilized soil structures and increased soil erosion (17). Based on average soil losses from arable land (18), the reduction in cropping area conferred by rbST use in one million cows would reduce soil erosion by 2.3×10^6 t per year.

Nutrient flows from animal production systems are of particular environmental concern: only a proportion of the cow's daily N (≈24%; ref. 19) and P (20–40%; ref. 20) intake is captured in milk, with the remainder excreted via feces and urine. Dairy manures therefore contain appreciable quantities of N and P in a ratio that is inefficient in meeting crop nutrient needs (20). Applying sufficient manure to fulfill N requirements (as is often practiced), may saturate the soil's P-holding capacity, allowing excess P to transfer into water courses via surface runoff and increasing the potential for eutrophication to occur. Water quality issues are further exacerbated by acidification resulting from wet deposition of NH_4^+, NO_2, and NO from ammonia and artificial fertilizers (21, 22). A significant proportion of manure N is lost through atmospheric ammonia volatilization, with further losses incurred through denitrification of nitrates to N_2O and N_2 (23). Improving productive efficiency is therefore invaluable in reducing nutrient flows associated with dairy production (16, 23). This is exemplified by the considerable reductions in N and P excretion (9.6×10^3 t per year and 4.3×10^3 t per year, respectively) that may be achieved with rbST supplementation (Table 2).

Carbon dioxide is recognized to be the most important anthropogenic greenhouse gas (24, 25), with emissions from animal agriculture resulting from two main sources: livestock metabolism and fossil fuel consumption. For one million rbST-supplemented cows, annual savings of 824×10^6 kg of CO_2, 41×10^6 kg of CH_4, and 9.6×10^3 kg of N_2O result from reductions in both population size and feedstuff production (Table 2). This is especially valuable because ruminants contribute 15–20% of global anthropogenic CH_4 emissions from enteric fermentation and manure (26). Although this may be altered by dietary manipulation (27, 28), the magnitude of such a decrease is unlikely to reach that achieved by rbST use. Reduced manure production from the smaller population would have a concomitant effect upon N_2O emissions that would be equally beneficial (Table 2); livestock-related activities are estimated to account for almost two-thirds of current anthropogenic N_2O emissions (27).

The global warming potential (GWP) is an index by which the environmental impact of a given mass of greenhouse gas can be compared on a CO_2 equivalent basis (24). Calculating the potential environmental effects of CH_4 and N_2O emissions as CO_2 equivalents is especially pertinent given the current focus on reducing individual "carbon footprints" by decreasing fossil fuel use and offsetting carbon emissions. The total reduction in GWP (CO_2 plus CO_2 equivalents from CH_4 and N_2O) conferred by rbST supplementation of one million dairy cows (Table 2) is equivalent to removing ≈400,000 family cars from the road (29) or planting ≈300 million trees (30). Carbon dioxide emissions from the rbST manufacturing process were not accounted for in this assessment, but they represent <1% of the savings conferred by rbST use (R.A.C., unpublished data).

Fossil fuel consumption raises two major environmental concerns: atmospheric pollution and resource sustainability (31). As a consequence of the reduced herd population and total feed requirement from rbST supplementation of one million cows, the energy required from fossil fuels (cropping only) and electricity for milk production is decreased by 729×10^6 MJ per year and 156×10^6 kilowatt hours (kWh) per year, respectively (Table 2). To put these figures into context, the savings in gasoline alone

Table 2. Current annual resources required for a population containing one million rbST-supplemented dairy cows and parameters relating to the environmental impact of producing the same quantity of milk without rbST supplementation

	Conventional	Conventional with rbST	Reductions with rbST use
Production parameters			
Milk production, kg/y $\times 10^9$	14.1	14.1	
Number of lactating cows*, $\times 10^3$	1,338	1,180	157
Number of dry cows, $\times 10^3$	217	192	25
Number of heifers, $\times 10^3$	1,291	1,139	152
Nutrient requirements			
Total maintenance energy requirement[†], MJ/y $\times 10^9$	54.1	47.8	6.3
Total maintenance protein requirement[†], t/y $\times 10^3$	667	606	61
Feedstuffs[‡], t freshweight/y $\times 10^6$	25.9	23.7	2.3
Waste output			
Nitrogen excretion, t/y $\times 10^3$	100	91	9.6
Phosphorus excretion, t/y $\times 10^3$	45.7	41.4	4.3
Manure, freshweight, t/y $\times 10^6$	34.9	32.2	2.8
Gas emissions			
Methane[§], kg/y $\times 10^6$	495	454	41
Nitrous oxide, kg/y $\times 10^3$	100	91	9.6
Carbon dioxide from livestock, kg/y $\times 10^6$	8,591	7,812	779
Carbon dioxide from cropping, kg/y $\times 10^6$	552	507	45
Carbon dioxide equivalents, (from CH_4 and N_2O), kg/y $\times 10^9$	12.4	11.4	1.0
Total global warming potential[¶], kg CO_2/y $\times 10^9$	21.6	19.7	1.9
Cropping inputs			
Cropping land required , ha $\times 10^3$	2,712	2,493	219
Nitrogen, kg/y $\times 10^6$	101	92	8.6
Phosphorus, kg/y $\times 10^6$	121	111	9.9
Potassium, kg/y $\times 10^6$	128	117	11
Herbicides, kg/y $\times 10^3$	1,953	1,790	163
Insecticides, kg/y $\times 10^3$	799	732	67
Fossil fuels[‖], MJ/y $\times 10^6$	8,840	8,111	729
Resource use			
Electricity, kWh/y $\times 10^6$	1350	1195	156
Water, liter/y $\times 10^9$	66.9	61.5	5.4

One million lactating cows supplemented with rbST plus associated ineligible lactating cows, dry cows and replacement heifers.

*Use of rbST significantly increases milk production (7); yield response to supplementation equaled 4.5 kg per day. The conventional with rbST group includes cows receiving rbST and those in early lactation that are not eligible for rbST supplementation.

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

[‡] Based on rations formulated to meet nutrient requirements using alfalfa hay, corn silage, corn grain and soybean meal as primary ingredients.

[§] Includes CH_4 from enteric fermentation and manure fermentation.

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

[‖] Only includes fuel used for cropping.

would be sufficient to power ≈1,550 passenger cars, each traveling an average of 12,500 miles per year (32). Furthermore, the total fossil fuel British thermal units (BTU) and electricity savings would provide sufficient annual heat and electricity for ≈16,000 and 15,000 households, respectively (33).

The national environmental impact of dairy production may be best assessed by considering broader indices of the environmental impact of milk production systems, which can then be applied to life cycle assessment (LCA), a method that considers resource inputs and environmental releases over the entire lifespan of a designated product (34). Previous LCA assessment of dairy products concluded that primary production is the major contributor to the total environmental impact (34); e.g., in cheese production, 95% of GWP, 99% of acidification potential (AP), eutrophication potential (EP), and 75% of total electricity and fossil fuel consumption occur at the farm level (35). Thus, the potential environmental impact of milk production systems may be evaluated simply by considering on-farm milk production. It is also necessary to consider the consumer perspective with regard to future U.S. requirements for sustainable milk production. The recent *Dietary Guidelines for Americans* (3) encourages increased consumption of fruits, vegetables, dairy products (fat-free and low-fat), and whole-grain foods, while staying within caloric recommendations. A substantial increase in milk production is required to meet dietary guidelines as the population increases: to meet the adult RDA of three 8-oz glasses milk per day for the year 2040, the annual quantity of milk produced in the U.S. would have to increase by >22 billion kg compared with 2006 production.

We compared three production systems: conventional, conventional with rbST, and organic. Responses to rbST supplementation are similar between production systems, but we did not analyze the impact of rbST in an organic production, because current U.S. guidelines do not allow its use (www.ams.usda.gov/nop/NOP/standards/ProdHandReg.html). In addition, we did not analyze the environmental impact of specific wastes from organic vs. conventional dairy systems, because these have been comprehensively covered elsewhere (21, 34, 36, 37).

Increased milk requirements necessitate a greater U.S. cow population but, relative to conventional systems, 8% fewer cows

Table 3. Projected environmental impact of different dairy management systems on the production of sufficient milk to meet USDHHS/USDA dietary guidelines

		Indexed*	
	Conventional	Conventional with rbST	Organic
Milk production[†], kg/y × 10^9	101	1.00	1.00
Lactating cows[‡] × 10^6)	6.58	0.92	1.25
Total dairy population[§] × 10^6)	14.0	0.92	1.25
Total land area required[¶], ha × 10^6	10.3	0.95	1.30
N excretion, t/y × 10^3	596	0.94	1.39
P excretion, t/y × 10^3	303	0.95	1.34
Eutrophication potential[‖], PO_4 equivalents), kg/y × 10^6	452	0.95	1.28
Acidification potential** (SO_2 equivalents), kg/y × 10^6	650	0.95	1.15
Global warming potential[††] (CO_2 equivalents), kg/y × 10^9	121	0.94	1.13

Total milk requirement calculated according to USDHHS/USDA (3) recommendations for adult dairy product intakes and U.S. Census Bureau (66) population estimate for 2040.

*Conventional values set to equal 1.0, and values for conventional with rbST or organic production systems are expressed according to this index.

[†] The conventional with rbST group includes rbST-supplemented lactating cows and cows in early lactation not yet eligible for rbST-supplementation (<57 days in milk). The conventional and organic groups include all lactating cows.

[§] Includes lactating cows, dry cows and replacement heifers.

[¶] Includes land area required for crop production (all groups) plus pasture (organic group only).

[‖] PO_4 equivalents based on $PO_4 = 1.00$, $N_2O = 0.44$ and $NH_4 = 0.43$.

**SO_2 equivalents based on $N_2O = 0.7$ and $NH_4 = 1.88$.

[††] CO_2 equivalents based on $CO_2 = 1$, $CH_4 = 25$ and $N_2O = 298$.

are needed in an rbST-supplemented population, whereas organic production systems require a 25% increase to meet production targets (Table 3). The greater number of animals needed to produce a comparable quantity of milk in the organic system results from lower milk yields per cow. This characteristic reduction in yield conferred by pasture-based systems can be attributed to a lack of an adequate supply of nutrients, especially metabolizable energy, and the greater maintenance energy expenditure associated with grazing behavior (38, 39).

Current U.S. organic dairy production standards stipulate that ruminants must "have access to graze pasture" and that "grazed feed must provide a significant proportion of total feed intake" (www.ams.usda.gov/nop/NOP/standards/ProdHandReg.html). Increased reliance on nutrients from pasture reduces cropland requirements, but this is negated by reduced organic crop yields (40), thus total land area is increased by 30% compared with equivalent milk production from conventional cows (Table 3).

Maintaining land as pasture has environmental advantages in terms of reduced soil erosion and nutrient leaching due to a more stable soil structure, undisturbed by tillage (41, 42). However, provision of dietary energy and protein is asynchronous in a pasture-based system, resulting in less efficient utilization of dietary protein and increased N excretion (39). Therefore, the combination of increased herd size, increased dietary P supply from pasture, and reduced efficiency of dietary N utilization results in a considerable increase in N and P excretion for organic dairy production systems (Table 3).

The environmental impact of the three production systems on water quality was assessed by calculating EP and AP (Table 3). The rbST-supplemented production system had the lowest EP and AP, 5% less than conventional milk production, whereas organic production practices augmented EP (28%) and AP (15%). This concurs with analysis by others comparing organic and conventional production systems, in which EP and AP were increased when expressed per unit of milk produced (36, 37, 43).

Animal agriculture contributes significantly to atmospheric CO_2 emissions, but rbST use reduced system GWP by 6.7 × 10^9 kg per year when compared with conventional production (Table 3). By contrast, organic production increased GWP by 15.7 × 10^9 kg per year compared with conventional production, concurring with a comparison of U.K.-based organic and conventional production systems (43).

Sustainability is an important consideration in agricultural production, with emphasis placed upon meeting human food requirements while mitigating environmental impact (5). The present study demonstrates that use of rbST markedly improves the efficiency of milk production and mitigates environmental parameters including EP, AP, greenhouse gas emissions, and fossil fuel use. Pretty (5) emphasized it is important to discard ideological principles and arguments against technologies *per se* and focus on opportunities for improvement offered through of a full range of modern biological approaches. This allows for dairy production systems centered on intensification of resources and use of current management practices and technologies to augment milk production while mitigating adverse effects upon the environment. Results of the present study clearly demonstrate that rbST is a biotechnology product that represents a valuable management tool for use in dairy production to increase productive efficiency and to have less negative effects on the environment than conventional dairying.

Methods and Assumptions

Model 1. The first model evaluated the environmental impact of rbST use on an individual cow basis, with comparisons expressed per unit of milk. Baseline milk yield for unsupplemented (conventional) cows was 9,050 kg per year (average milk production per cow in the U.S. for 2006; www.ers.usda.gov/publications/ldp). This was equivalent to 28.9 kg per day when adjusted for a 14-mo calving interval (426 d) and a 60-d dry period, determined as 2006 industry standards based on a weighted average of data published by the U.S. Department of Agriculture (USDA) (44) and a survey of DairyMetrics data (45). Milk fat (3.69%) and true protein (3.05%) represented the U.S. averages for 2006 (46). Supplementation with rbST was modeled according to FDA-approved guidelines (POSILAC, Monsanto), with administration commencing at 57 d postpartum and continuing every 14 d until the end of lactation. Under these guidelines, a cow is eligible for 21.1 doses of rbST per lactation or 18.3 on an annual prorated basis. Milk yield response to rbST was based on data that demonstrated a central tendency toward 4.5 kg per day (47–51).

Nutrient requirements were calculated according to National Research Council (NRC; ref. 38) recommendations based on an average multiparous cow at 650 kg of body weight and 45 mo of age. Mowrey and Spain (11) reported that alfalfa hay, corn silage, dry ground corn grain, and soybean meal were the most commonly used diet ingredients for U.S. dairy herds. Using these as primary ingredients, rations for lactating cows were formulated to meet requirements at predicted dry matter intakes (DMI) according to NRC (38) recommendations for maintenance and milk production. A diet digestibility of 65% was used to calculate manure output at 15% dry matter (52). Daily CH_4 production from enteric fermentation was calculated according to the equation derived by Moe and Tyrrell (53) based on the characteristics of the diet. Emissions of CH_4 from stored manure were estimated using the formula reported by the U.S. Environmental Protection Agency (EPA; ref. 54) based on the quantity of volatile solids excreted, maximum CH_4-producing potential (0.24 cubic meters per kg of volatile solids), and a CH_4 conversion factor (21.7) for liquid systems. Daily N excretion was calculated by subtracting its output in milk ($n = 6.38\%$ of milk true protein) from the dietary N supply ($n = 6.25\%$ of dietary crude protein). Phosphorus excretion was derived from P intake via the equation developed by Nennich *et al.* (55).

Model 2. The environmental impact of one million lactating dairy cows receiving rbST annually was evaluated by using current industry productivity benchmarks. Baseline milk yield and composition, milk yield response to rbST supplementation, ration formulation, and the calculation of manure, CH_4, N, and P outputs were as described for Model 1. Using the same performance standards for milk production and reproduction and assuming the lack of any seasonal calving pattern, it was determined that at any point in time, 14.1% of a dairy cow herd would be dry, 13.1% would be lactating but ineligible for rbST supplementation, and rbST-supplemented lactating cows would comprise the remaining 72.8% of the modeled population. Environmental impact was calculated by comparing annual resource inputs and waste output of a population containing one million rbST-supplemented cows, to a comparably managed conventional population of increased size required to produce the same volume of milk.

A change in the size of a milking cow population requires a concomitant change in the replacement heifer population to sustain the population over the longer term. Previous data indicate that rbST use has no significant impact on culling (49, 50); therefore, no adjustment in replacement rate was required. Replacement heifer numbers were modeled based on the aforementioned calving interval, an average age at first calving of 25.5 mo (44), a sex ratio at birth of 49% females (56), a twinning ratio of 5% (57, 58), and published heifer mortality rates (44). The resulting index of 0.83 heifers per cow (milking and dry) was estimated by using USDA data (www.ers.usda.gov/publications/ldp) and was in agreement with the value of 0.83 published by DairyMetrics (45).

Dry cow diets were formulated for requirements at 250 days of gestation and heifer rations formulated based on an average heifer at 12 mo of age, 277 kg of live weight, and 720 g average daily gain (38, 59). The equation developed for lactating cows by Nennich *et al.* (55) overpredicted dry cow and heifer P excretion; therefore, this was calculated as dietary intake minus requirements for pregnancy and growth.

Manure N_2O emissions were calculated as 0.001 kg of N_2O per kg of N excreted (54). The GWP of CO_2, CH_4, and N_2O were based on CO_2 equivalent factors for a 100-year time period with $CO_2 = 1$, $CH_4 = 25$, and $N_2O = 298$ (24). Carbon dioxide emissions from the animals were calculated based on body weight and milk production according to the equation of Kirchgessner *et al.* (60). Fuel CO_2 emissions from combustion were calculated according to carbon content and efficiency of combustion (29). Crops under conventional tillage were not considered to sequester carbon additional to that emitted through agronomy practices (61).

Average yields and usage of fertilizer (N, P, and K) and pesticides for dietary ingredients were taken from USDA data from 2005 (corn) and 2001 (soybeans) (www.ers.usda.gov/Data/ARMS/app/Crop.aspx). Figures for fuel usage (gasoline, diesel, liquified petroleum gas, natural gas, and electricity) for corn and soybean production were based on Foreman (62) and Foreman and Livezey (63), respectively. The factor conversion from soybeans to soybean meal was 80%.[¶] Average alfalfa yields were taken from USDA (www.nass.usda.gov) with inputs for alfalfa production derived from Pimentel and Pimentel (64). Estimates of soil loss from erosion were calculated from USDA/National Resources Conservation Service (18) with annual losses of 4.7 and 5.6 t per ha from wind erosion and water erosion, respectively.

Total water use comprised the herd's free water intake estimated according to Holter (65) and water use for sanitation at a rate of 28.4 liters per day (lactating cows only).[‖] Annual electricity use for cattle housing (e.g., lighting and ventilation) was 326 kW per animal, with an additional 247 kW per lactating cow for milk cooling, and storage (www.ansci.cornell.edu/prodairy).

Model 3. *Dietary Guidelines for Americans* (3) recommend an increase in dairy product consumption; the third model evaluated the environmental impact of meeting this increased milk requirement under different management systems: conventional, conventional with rbST, and organic production. The total milk requirement was calculated according to the predicted U.S. population of 377 million people for the year 2040 (66) with a daily milk intake of three 8-oz servings as recommended by U.S. Department of Health and Human Services (USDHHS)/USDA (3). Projected annual milk and crop yields for the year 2040 were estimated by using a simple linear regression of annual yield data for all years from 1956 to 2006 (www.nass.usda.gov) to determine an annual increment of yield per cow (milk) and per hectare (crops). Average annual increases were 123 kg of milk ($r^2 = 0.93$), 20 kg of corn ($r^2 = 0.92$), 4.2 kg of soybeans ($r^2 = 0.96$), 58 kg of corn silage ($r^2 = 0.97$), and 9.6 kg of alfalfa hay ($r^2 = 0.98$). Milk composition, response to rbST, nutrient requirements, and waste output were calculated for conventional and rbST-supplemented cows as described for Models 1 and 2.

Annual milk yields are significantly decreased under organic management, and we used a value 20% lower than that of conventional systems, based on reported reductions in yield ranging from 14.3% to 26.2% (43, 44, 67, 68). Because of a paucity of available data, the proportion of heifers and dry cow equivalents within the herd was assumed to be equal to those reported for conventional production. Diets for lactating cows and heifers in the organic production system were formulated according to the NRC (38), with 50% of DMI provided by pasture and the remaining nutrients provided from organically produced feedstuffs as used in the conventional system. To avoid oversupplying energy and protein, dry cow diets were based on 20% of DMI provided from pasture. A stocking rate of 2.3 cows per ha, recommended as the optimum for pasture use on Northeast U.S. dairy farms (69), was used to calculate total pasture requirements. Adjustment factors of 0.92, 0.92, and 0.83 were used to model crop yields from corn grain/silage, alfalfa, and soybeans, respectively, compared with conventional crop production (www.ers.usda.gov/Data/ARMS/app/Crop.aspx; ref. 40).

Reference values for ammonia emissions were taken from Rumburg *et al.* (70). System EP was calculated as the sum of PO_4 equivalents estimated using coefficients for PO_4 (1.00), N_2O (0.44), and NH_3 (0.43), as described by Williams *et al.* (43). Similarly, AP was defined as the sum of SO_2 equivalents produced by multiplying N_2O and NH_3 by their respective SO_2 coefficients ($N_2O = 0.70$; $NH_3 = 1.88$) as reported by Ogino *et al.* (71). Calculations of EP and AP were based on emissions from animals and manure only. Results relating to the environmental impact of conventional with rbST or organic production systems were expressed as an index relative to the conventional system.

[¶] Toride Y, Expert Consultation and Workshop, April 23–May 3, 2002, Bangkok, Thailand.

[‖] Brugger M, American Society of Agricultural and Biological Engineers, Annual International Meeting, July 9–12, 2006, Portland, OR, paper no. 064035.

ACKNOWLEDGMENTS. This work was supported in part by funding provided by the Liberty Hyde Bailey Professorship in College of Agriculture and Life Sciences at Cornell University and by the Cornell Agricultural Experiment Station.

1. United Nations Population Division (2005) *Long-Range World Population Projections: Based on the 1998 Revision* (United Nations Population Division, New York).
2. Bauman DE (1992) Bovine somatotropin: Review of an emerging animal technology. *J Dairy Sci* 75:3432–3451.
3. US Department of Health and Human Services and US Department of Agriculture (2005) *Dietary Guidelines for Americans 2005* (US Government Printing Office, Washington, DC), 6th Ed.
4. Buzby JC, Wells HF, Vocke G (2006) *Possible Implications for U.S. Agriculture from Adoption of Select Dietary Guidelines. Economic Research Report no. 31* (US Department of Agriculture, Washington, DC).
5. Pretty J (2008) Agricultural sustainability: Concepts, principles and evidence. *Philo Trans R Soc London Ser B* 363:447–465.
6. Bauman DE (1999) Bovine somatotropin and lactation: From basic science to commercial application. *Domes Anim Endocrinol* 17:101–116.
7. National Research Council (1994) *Metabolic Modifiers: Effects on the Nutrient Requirements of Food-Producing Animals* (Natl Acad Press, Washington, DC).
8. Johnson DE, Ward GM, Torrent J (1992) The environmental impact of bovine somatotropin use in dairy cattle. *J Environ Qual* 21:157–162.
9. Bauman DE, McCutcheon SN, Steinhour WD, Eppard PJ, Sechen SJ (1985) Sources of variation and prospects for improvement of productive efficiency in the dairy cow: A review. *J Anim Sci* 60:583–592.

10. VandeHaar MJ, St-Pierre N (2006) Major advances in nutrition: Relevance to the sustainability of the dairy industry. *J Dairy Sci* 89:1280–1291.
11. Mowrey A, Spain JN (1999) Results of a nationwide survey to determine feedstuffs fed to lactating dairy cows. *J Dairy Sci* 82:445–451.
12. Van Horn HH, Newton GL, Kunkle WE (1996) Ruminant nutrition from an environmental perspective; Factors affecting whole-farm nutrient balance. *J Anim Sci* 74:3082–3102.
13. Steinfeld H, *et al.* (2006) *Livestock's Long Shadow: Environmental Issues and Options* (Food and Agriculture Organization, Rome).
14. Jonker JS, Kohn RA, High J (2002) Dairy herd management practices that impact nitrogen utilization efficiency. *J Dairy Sci* 85:1218–1226.
15. Dunlap TF, Kohn RA, Dahl GE, Varner M, Erdman RA (2000) The impact of somatotropin, milking frequency and photoperiod on dairy farm nutrient flows. *J Dairy Sci* 83:968–976.
16. Bosch DJ, Wolfe ML, Knowlton KF (2006) Reducing phosphorus runoff from dairy farms. *J Environ Qual* 35:918–927.
17. Montgomery DR (2007) Soil erosion and agricultural sustainability. *Proc Natl Acad Sci USA* 104:13268–13272.
18. US Department of Agriculture/National Resources Conservation Service (2007) *2003 Annual National Resources Inventory: Soil Erosion* (US Department of Agriculture, Washington, DC).
19. Kohn RA, Dou Z, Ferguson JD, Boston RD (1997) A sensitivity analysis of nitrogen losses from dairy farms. *J Environ Manage* 50:417–428.
20. Knowlton KF, Radcliffe JS, Novak CL, Emmerson DA (2004) Animal management to reduce phosphorus losses to the environment. *J Anim Sci* 82:E173–E195.
21. Thomassen MA, Van Calker KJ, Smits MCJ, Iepema GL, de Boer IJM (2008) Life cycle assessment of conventional and organic milk production in the Netherlands. *Agr Syst* 96:95–107.
22. Camargo JA, Alonso A (2006) Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. *Environ Int* 32:831–849.
23. Rotz CA (2004) Management to reduce nitrogen losses in animal production. *J Anim Sci* 82:E119–E137.
24. Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: The Physical Basis* (Intergovernmental Panel on Climate Change, Geneva).
25. Lassey KR (2007) Livestock methane emission: From the individual grazing animal through national inventories to the global methane cycle. *Agric For Meteor* 142:12–132.
26. National Research Council (2003) *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs* (Natl Acad Press, Washington, DC).
27. Council for Agricultural Science and Technology (2004) *Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture. Task Force Report no. 141* (Council for Agricultural Science and Technology, Ames, IA).
28. Grainger C, *et al.* (2008) Use of Monensin controlled-release capsules to reduce methane emissions and improve milk production of dairy cows offered pasture supplemented with grain. *J Dairy Sci* 91:1159–1165.
29. US Environmental Protection Agency (2007) *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2005. Annex 2: Methodology and Data for Estimating* CO_2 *Emissions from Fossil Fuel Combustion* (US Environmental Protection Agency, Washington, DC).
30. Sampson RN, Hair D, Eds (1996) *Forests and Global Change* (American Forests, Washington, DC), Vol II.
31. Edinger R, Kaul S (2000) Humankind's detour towards sustainability: Past, present, and future of renewable energies and electric power generation. *Renew Sust Energy Rev* 4:295–313.
32. Energy Information Administration (2004) *Motor Vehicle Mileage, Fuel Consumption and Fuel Rates, 1949-2004* (Energy Information Administration, Washington, DC).
33. Energy Information Administration (2001) *Total Energy Consumption in U.S. Households by Urban/Rural Location, 2001* (Energy Information Administration, Washington, DC).
34. Foster C, *et al.* (2006) *Environmental Impacts of Food Production and Consumption: A Report to the Department for Environment, Food and Rural Affairs* (Manchester Business School/Department for Environment, Food, and Rural Affairs, London).
35. Berlin J (2002) Environmental LCA of Swedish hard cheese. *Int Dairy J* 12:939–953.
36. Cederberg C, Mattsson B (2000) Life cycle assessment of milk production–A comparison of conventional and organic farming. *J Clean Prod* 8:49–60.
37. de Boer IJM (2003) Environmental impact assessment of conventional and organic milk production. *Livest Prod Sci* 80:69–77.
38. National Research Council (2001) *Nutrient Requirements of Dairy Cattle* (Natl Acad Press, Washington, DC), 7th Ed.
39. Kolver ES (2003) Nutritional limitations to increased production on pasture-based systems. *Proc Nutr Soc* 62:291–300.
40. Porter PM, Huggins DR, Perillo CA, Quiring SR, Crookston RK (2003) Organic and other management strategies with two- and four-year crop rotations in Minnesota. *Agron J* 95:233–244.
41. Allen VG, *et al.* (2008) In search of sustainable agricultural systems for the Llano Estacado of the U.S. Southern High Plains. *Agr Ecosyst Environ* 124:3–12.
42. Hobbs PR, Sayre K, Gupta R (2007) The role of conservation agriculture in sustainable agriculture. *Philos Trans R Soc London Ser B* 363:543–555.
43. Williams AG, Audsley E, Sandars DL (2006) *Determining the Environmental Burdens and Resource Use in the Production of Agricultural and Horticultural Commodities. DEFRA Research Project ISO205* (Department for Environment, Food, and Rural Affairs, London).
44. US Department of Agriculture (2007) *Dairy 2007 Part 1: Reference of Dairy Cattle Health and Management Practices in the United States, 2007* (US Department of Agriculture, Washington, DC).
45. Dairy Records Management Systems (2008) *DairyMetrics Report.* (Dairy Records Management Systems, Raleigh, NC).
46. US Department of Agriculture/Agricultural Monitoring Service (2007) *Federal Milk Order Market Statistics 2006* (US Department of Agriculture, Washington, DC).
47. Hartnell GF, *et al.* (1991) Evaluation of sometribove in a prolonged-release system in lactating dairy cows–Production responses. *J Dairy Sci* 74:2645–2663.
48. Pell AN, *et al.* (1992) Effects of a prolonged-release formulation of sometribove (*n*-methionyl bovine somatotropin) on Jersey cows. *J Dairy Sci* 75:3416–3431.
49. Ruegg PL, Fabellar A, Hintz RL (1998) Effect of the use of bovine somatotropin on culling practices in thirty-two dairy herds in Indiana, Michigan and Ohio. *J Dairy Sci* 81:1262–1266.
50. Bauman DE, Everett RW, Weiland WH, Collier RJ (1999) Production responses to bovine somatotropin in northeast dairy herds. *J Dairy Sci* 82:2564–2573.
51. Collier RJ, *et al.* (2001) Effects of sustained release bovine somatotropin (Sometribove) on animal health in commercial dairy herds. *J Dairy Sci* 84:1098–1108.
52. Dado RG, Allen MS (1995) Intake limitations, feeding behavior and rumen function if cows challenged with rumen fill from dietary fiber or inert bulk. *J Dairy Sci* 78:118–133.
53. Moe PW, Tyrrell HF (1979) Methane production in dairy cows. *J Dairy Sci* 62:1583–1586.
54. US Environmental Protection Agency (2007) *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2005. Annex 3: Methodological Descriptions for Additional Source or Sink Categories* (US Environmental Protection Agency, Washington, DC).
55. Nennich TD, *et al.* (2005) Prediction of manure and nutrient excretion from dairy cattle. *J Dairy Sci* 88:3721–3733.
56. Cady RA, Van Vleck LD (1978) Factors affecting twinning and effects of twinning in Holstein dairy cattle. *J Anim Sci* 46:950–956.
57. Johanson JM, Berger PJ, Kilpatrick BW, Dentine MR (2001) Twinning rates for North American Holstein sires. *J Dairy Sci* 84:2081–2088.
58. Silva del Rio N, Stewart S, Rapnicki P, Chang YM, Fricke PM (2007) An observation analysis of twin births, calf sex ratio, and calf mortality in Holstein dairy cattle. *J Dairy Sci* 90:1255–1264.
59. Heinrich J, Lammers B (1998) *Monitoring Dairy Heifer Growth* (Pennsylvania State University, University Park, PA).
60. Kirchgessner M, Windisch W, Müller HL, Kreuzer M (1991) Release of methane and of carbon dioxide by dairy cattle. *Agribiol Res* 44:2–9.
61. West TO, Marland G (2002) A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. *Agric Ecosys Environ* 91:217–232.
62. Foreman L (2006) *Characteristics and Production Costs of US Corn Farms, 2001. USDA Economic Research Service Economic Information Bulletin Number 7* (US Department of Agriculture Economic Research Service, Washington, DC).
63. Foreman L, Livezey J (2002) *Characteristics and Production Costs of US Soybean Farms. USDA Statistical Bulletin Number 974-4* (US Department of Agriculture Economic Research Service, Washington, DC).
64. Pimentel A, Pimentel M (1996) *Food Energy and Society* (Univ Press of Colorado, Boulder, CO).
65. Holter JB (1992) Water partitioning and intake prediction in dry and lactating Holstein cows. *J Dairy Sci* 75:1472–1479.
66. US Census Bureau (2000) *Annual Projections of the Total Resident Population, as of July 1: Middle, Lowest and Highest, and Zero International Migration Series, 1999 to 2100* (US Census Bureau, Washington, DC).
67. Zwald AG, *et al.* (2004) Management practices and reported antimicrobial usage on conventional and organic dairy farms. *J Dairy Sci* 87:191–201.
68. Sato K, Bartlett PC, Erskine RJ, Kaneene JB (2005) A comparison of production and management between Wisconsin organic and conventional herds. *Livest Prod Sci* 93:105–115.
69. McCall DG, Clark DA (1999) Optimized dairy grazing systems in the Northeast United States and New Zealand. II. System Analysis. *J Dairy Sci* 82:1808–1816.
70. Rumburg B, Mount GH, Filipy J, Lamb B, Westberg H (2008) Measurement and modeling of atmospheric flux of ammonia from dairy milking cow housing. *Atmos Environ* 42:3364–3379.
71. Ogino A, Katu K, Osada T, Shimada K (2004) Environmental impacts of the Japanese beef-fattening system with different feeding lengths as evaluated by a life-cycle assessment method. *J Anim Sci* 82:2115–2122.