

# **Methane, nitrous oxide and carbon dioxide emissions from ruminant livestock production systems**

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## **Summary**

System inputs with greenhouse gas (GHG) implications were summarized for typical U.S. beef production systems and for representative U.S. and N.Z. dairy systems. The GHG emissions are expressed in carbon dioxide equivalents (CO<sub>2</sub>eq) and related to livestock system product output. The U.S. beef systems are estimated to produce from 13 to 16 kg of CO<sub>2</sub>eq per kg of live weight sold and the dairy systems 1.3 kg of CO<sub>2</sub>eq/kg of milk while the pasture based N.Z. dairies produced 1.6 kg/kg milk. Relative source strengths varied. Nitrous oxide was the largest CO<sub>2</sub>eq source of beef system emissions, 52%, with 36 and 12% from methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>). The amount of methane per wt sold was quite uniform across location in the U.S., while nitrous oxide was variable ranging from 7 in WI to 9 kg CO<sub>2</sub>eq/kg sold in TX. Methane was the largest CO<sub>2</sub>eq source from CA dairies, while nitrous oxide (N<sub>2</sub>O) was the largest in N.Z. dairies. High CH<sub>4</sub> in CA was due to extensive use of anaerobic lagoon disposal of manure while excess N content and flux on N.Z. pastures caused higher relative N<sub>2</sub>O emissions. Utilization of best management practices and manure amendments to sequester carbon in the crop and forage land of ruminant livestock production systems have modest potential to offset their GHG emissions.

*Keywords: greenhouse gas, cattle, production system*

## **Introduction**

The unique gastrointestinal tract of ruminants coupled with large populations and/or body size, and appetites, results in annual global atmospheric emissions of about 77 Tg of methane enterically and 7 Tg from manure handling systems. Inventories and mitigation proposals of GHG's release from livestock have usually emphasized the enteric source (e.g., RLEP, 1998). Additional investigations of overall production systems, however, show other important sources (Ward et al., 1993; Johnson et al., 1997). With the more complete source estimates of N<sub>2</sub>O (Mosier et al., 1998) as recommended for inventory purposes by IPCC (2000), the livestock production system emissions as carbon dioxide equivalents (N<sub>2</sub>O-CO<sub>2</sub>eq) of some systems exceeded those for CH<sub>4</sub> (Johnson et al., 2000b). Robertson et al. (2000) found N<sub>2</sub>O to be the single greatest source of CO<sub>2</sub>eq emissions from nearly all agronomic systems in Midwest U.S. observations. This paper briefly reviews and updates prior summaries (Johnson et al., 2000a, 2001) including embodied CO<sub>2</sub> inputs and expands coverage of management and mitigation strategy effects on cattle production system variations and relative source strengths of GHG emissions. Details of systems spreadsheet assumptions can be found in a report to E.P.A. (Johnson et al., 2000a) or by query to the authors.

## **Estimation procedures**

Beef and dairy systems were divided into 6 to 16 classes based on age, physiological or production stage, e.g., replacement animals, lactation, etc. The systems are based on the maintenance of and output from 100 head of mature cows. Inputs and outputs for each class

were described from national (National Agricultural Statistics Service, National Animal Health Monitoring System), state (Cooperative Extension Service) and industry (National Cattlemen's Beef Assoc., Cattle-Fax) sources. Comparable information from the Livestock Improvement Corporation (LIC) and the Meat and Wool Economic Service (MWB) were consulted for New Zealand. Stocker cattle (weaned calves prior to feedlot) from each location were fed out in one of two representative feedlots, Texas (TX) or Iowa (IA). Production characteristics for each system include mature weights, mortality, culling, calving, replacement and growth rates, and live weight of beef output at the farm gate (Table 1). Dietary requirements and enteric CH<sub>4</sub> emissions were derived per IPCC (2000) Good Practice Inventory guidelines, an adaptation of NRC (1989, 1996) net energy requirements. Key assumptions include, 6 % of diet energy loss as methane generally, except for 3.5 % for the feedlot phase. Nitrous oxide estimates were 1.25 % of crop N-fertilization, and up to 2.5 % from manure or leached N. Carbon dioxide emissions from fertilizer synthesis and fossil fuel use for cropping, transportation, insecticide and herbicide synthesis and application, are based on Pimentel et al. (1980) in the U.S. and Wells (1998) in N.Z.. Methane and nitrous oxide were converted to CO<sub>2</sub>eq using the factors of 21 and 310 g/g (IPCC, 1996). Local sources were used to define typical feedstuff ingredients, crop production practices and yields, fertilizer, insecticide and herbicide applications, manure handling, fuel use for crops, irrigation, transport, feed grain processing, cost of production for feed and animal management, and revenue (U.S. only) from cattle or milk sold (see partial list in Table 1). Byproduct feeds are apportioned to cropping inputs relative to \$ value of the crop product(s). The CO<sub>2</sub> emission estimates are based on U.S. practices (Pimentel, 1980) with diesel as the fuel of choice.

The U.S. dairy cows averaged 613 kg live weight, 37% replacement rates and 11 mo lactations, producing 7200 to 9000 kg of milk annually containing 3.5% fat and 3.3% protein. The U.S. systems are dry lot, or 'mixed' operations with pasture comprising 0 to 31 % of the herd diet (Table 1). Alfalfa hay, corn silage, cereal grains, soybean meal and byproducts constituted the principal diet ingredients, averaging 10.5 MJ ME/kg DM in the U.S.. Anaerobic lagoon disposal was used for 50% of the manure in California (CA) and very little in Wisconsin (WI). Fertilizer application rates ranged from 27 to 91 kg of N and 13 to 18 kg of P per ha.

The New Zealand pasture based dairy was characterized as a Holstein herd of cows weighing 511 kg producing 3444 kg of milk with 4.34% fat and 3.41% protein during a 270 day lactation annually (LIC, 1999) with a 15% replacement rate (MWB NZ, 1999). Mortality rates of 1.3% for cows (Holmes, 1999) and 4 to 5% for heifers and calves were assumed. The diet contained 10.1 MJ ME/kg DM, 80 to 85 % from pasture, with the balance being haylage and a small fraction of maize silage. Pasture yields were 12 T DM/ha with fertilizer applications of 63 and 78 kg on N and P/ha (Wilcock et al., 1999) and no irrigation. Manure was applied to pasture, primarily by grazing animals, with 3% disposed through anaerobic lagoons at milk sheds (Russell, 1999).

## Results and discussion

The 100 cow beef systems, cow-calf through feedlot, produced 37 t of live weight sales annually, which includes 9 t from cull cows and bulls (Table 1). Their diet was composed of 55 % pasture and 20% hay. These totals include the feedlot phase that used no pasture and only 10 to 20% forage. Manure (10 t of manure N per herd) was disposed on pastures for the cow-calf and stocker phases and by drylot methods from the feedlots. Land requirements (ha) for the herds, stockers and feedlot cattle from these five U.S. counties with large numbers of beef cows averaged 315 ha (range, 122 to 745). Nitrogen fertilizer use averaged 2.2 t/herd with moderate variation by location.

*Table 1. Characteristics of simulated U.S. beef cow-calf through feedlot, U.S. and N.Z. dairy production systems.*

Characteristics (100-cow herds)	U.S. Beef	U.S. Dairies		New Zealand Dairy
	Average (CV %)	CA	WI	
Mature cow weight, kg	497 (2)	635	590	511
Cows, calves, replacements, hd	168 (1)	167	180	127
Replacement, %	16 (5)	33	40	15
Calving rate, %	92 (3)	93	93	96
Calf mortality, to wean, %	10 (42)	9.1	10.8	9.0
Adult mortality, %	1.4 (64)	5.0	3.8	1.3
Live weight sold, t	37 (4)	21.3	23.2	18.3
Milk sold, kg/cow	0	8982	7169	3444
Pasture, %	55 (8)	0	31	81
Other roughage, %	20 (45)	43	30	15
Total ha/herd	315 (85)	103	166	41
Nitrogen, syn., 10 <sup>3</sup> kg	2.2 (35)	9.3	4.4	2.6
Fuel, herd, 10 <sup>3</sup> l	10 (13)	34	30	4
Manure on pasture, %	89 (.4)	0	42	94
Manure, anaerobic lagoon, %	0	50	3	3

CV = coefficient of variation; CA = California; WI = Wisconsin

The GHG emissions, as CO<sub>2</sub>eq, averaged 580 t (CV=7%) from the cow-calf through feedlot beef production units (Table 2). These U.S. beef systems averaged 15.5 kg CO<sub>2</sub>eq/kg of live weight produced. The emissions are predominantly from the cow-calf phase (77%) with lesser amounts from the stocker (11%) and feedlot (12%) phases. Division by gas source, shows approximately 36% from CH<sub>4</sub>, 52% from N<sub>2</sub>O, and the balance from CO<sub>2</sub>. Manure disposal accounted for a small fraction of the CH<sub>4</sub> emissions since none of the beef systems simulated used anaerobic lagoons, however, manure from grazing or use for fertilizer produced a large part of the N<sub>2</sub>O emissions. Nitrous oxide emission equivalents were the most variable among locations (CV = 33 %).

Total CO<sub>2</sub>eq emissions from the 100-cow U.S. dairy systems were about double those from the beef systems, and 80 to 100% higher than 100-cow N.Z. dairies (Table 2). When expressed as CO<sub>2</sub>eq/product, however, the N.Z. herd emissions of 1.62 kg/kg of milk were slightly greater. These dairy system estimates are higher than found by Cedarberg (1998) who reported 1.0 kg CO<sub>2</sub> equivalent per kg milk on a whole farm or 'life cycle' basis for conventional dairy farms in Sweden.

The CA dairy has the lowest CO<sub>2</sub>eq/milk even with a larger amount of methane production from the 50% of manure disposal via anaerobic lagoons. Comparison of the dairies according to enteric CH<sub>4</sub> per unit of milk, shows even more advantage to the CA dairy, which produces 12% less than those in WI and 40% less than those in N.Z.. This comparison illustrates the strong effect of increasing productivity per cow resulting in reduced feed requirements and thus GHG output per unit of milk. Examination of the fractional source of these varying amounts of GHG's also shows considerable variation by production system.

The CH<sub>4</sub>-CO<sub>2</sub>eq was the single largest contributor, 45%, in the CA dairy system with N<sub>2</sub>O-CO<sub>2</sub>eq and CO<sub>2</sub> contributing similar proportions of the balance of GHG emissions. In WI, CO<sub>2</sub> emissions contributed the most CO<sub>2</sub>eq at 40% of the total emissions while CH<sub>4</sub> and

N<sub>2</sub>O-CO<sub>2</sub>eq were approximately equal. The N.Z. system was different in that the largest single source was N<sub>2</sub>O-CO<sub>2</sub>eq at 47% with 40% contributed from CH<sub>4</sub>-CO<sub>2</sub>eq. The N.Z. system was also unique in that only 13% of the GHG's were from CO<sub>2</sub>, a reflection of dependence on hydroelectric power sources.

*Table 2. Source strengths of beef and dairy GHG emissions (annual CO<sub>2</sub>eq).*

Source of GHG	U.S. Beef Cow-	CA Dairy CO <sub>2</sub> eq	WI Dairy CO <sub>2</sub> eq	N.Z. Dairy CO <sub>2</sub> eq
	Feedlot CO <sub>2</sub> eq Mean (%CV)			
<b>Enteric CH<sub>4</sub>:</b>				
t per herd	206 (10)	320	292	207
kg/kg product	5.5 (0.3)	0.36	0.41	0.60
<b>Manure CH<sub>4</sub>:</b>				
t per herd	5.2 (1.5)	185	18	16
kg/product	0.14 (0.4)	0.21	0.03	0.04
<b>N<sub>2</sub>O:</b>				
t per herd	301 (33)	330	298	259
kg/product	8.1 (0.9)	0.37	0.42	0.76
<b>CO<sub>2</sub>:</b>				
t per herd	67 (11)	296	407	74
kg/product	1.8 (0.3)	0.33	0.57	0.22
<b>Total GHG:</b>				
t per herd	580 (6.8)	1130	1015	556
kg/product	15.5 (1.0)	1.26	1.38	1.62
t per ha	1.8 (1.5)	11.0	6.2	13.6

Nitrous oxide emissions are inherently highly variable (Mosier et al., 1998) and were estimated by IPCC (2000) methods. Nitrous oxide (CO<sub>2</sub>eq) emissions ranged from 301 to 330 t per 100-cow beef or dairy herds (Table 3). From 16 to 54% of the N<sub>2</sub>O emissions resulted from manure application or deposition during grazing. A second source, about 30% is from indirect emissions of leached, gaseous, or runoff-N. Other sources include legumes, crop residues and manure management. Nitrous oxide emissions are likely to be even more variable than indicated by this analysis because of variations by N application rates to soils, season, soil type, ambient temperature, soil moisture, etc.

*Table 3. Nitrous oxide emission sources (t CO<sub>2</sub>eq/100-cow herd) from U.S. cattle and N.Z. dairy production systems.*

N <sub>2</sub> O Sources	United States			New Zealand
	Beef	CA dairy	WI dairy	Dairy
Annual t N <sub>2</sub> O-CO <sub>2</sub> eq				
Synthetic fertilizer	12	51	24	15
Manure <sup>a</sup>	45	67	37	4
Manure management	10	70	28	0
Legume	6.3	29	43	5
Crop residue <sup>b</sup>	42	6	34	13
Grazing	90 ✓	0	43	139
Volatilized	19	19	17	16
Leaching	76	88	72	66
Total N <sub>2</sub> O, t/herd	301	330	298	260

<sup>a</sup>Includes animal waste and broiler litter.

<sup>b</sup>Includes waste grass.

Total annual N<sub>2</sub>O emissions expressed per land range from 0.4 from the UT beef system to 6.4 t N<sub>2</sub>O-CO<sub>2</sub>eq/ha from the N.Z. dairy. The higher emissions are considerably above the 2.4 and 2.6 t N<sub>2</sub>O-CO<sub>2</sub>eq ha<sup>-1</sup>yr<sup>-1</sup> noted previously for N.Z. grasslands (Sherlock et al., 1992) and Dutch dairy systems (Velthof and Oenema, 1997). The higher emissions likely reflect the increased emphasis of IPCC (2000) default estimates for leached nitrogen (30% of manure and fertilizer applied to soil) plus the inclusion of emission estimates from the N in grass residue.

### **Management and/or mitigation strategy effects:**

The variations in resource inputs and outputs from the dairy systems provide interesting insights to causes of variations in CO<sub>2</sub>eq/product. Such variations in production or management techniques may serve as mitigation options. The magnitude of variations in GHG sources per milk vary from 2-fold for nitrous oxide to 8-fold for manure methane by production system. The wide range in manure methane emissions reflects the heavy dependence on anaerobic lagoon disposal used in the CA systems, resulting in 16% of CO<sub>2</sub>eq from this source as compared to 3 to 2% from N.Z. and WI systems, respectively. Not surprisingly, anaerobic lagoon use for manure disposal is the most obvious target for GHG mitigation because of the major increases in methane and some increases in nitrous oxide emissions.

The dairy systems comparison reveals what appears to be a major limitation of pasture-only dairy production systems, the reduced milk production per cow, resulting in a higher feed and methane cost associated with the higher proportion of feed going to maintenance. This limitation occurs in spite of the approximately equal concentration of available energy (Mcal of ME/kg diet DM) in the pastures of N.Z. as found in the concentrate containing diets in the U.S.. Ruminant nutritionists feel that the bulky, high moisture nature of grass causes the limitation to daily energy consumption and thus milk production of these cows since the genetic potential to produce milk has been shown to be approximately equal in U.S. and N.Z. cows. If the CA cows produced only as much fat plus protein in their milk as the N.Z. cows/yr, and lagoon use kept about equal, the CA GHG emissions per unit milk would increase about 73%. Conversely, if N.Z. cows could eat enough grass and produce as much milk fat and protein annually as the CA cows, the GHG emissions per unit milk would fall 37%. Such factors can be illustrated with our model comparisons.

If the body weights are all equalized to the heaviest cows (e.g. 635 kg as in CA), the emissions/milk increase 3% in WI and 15% in N.Z., other things being equal. Thus increasing annual milk per cow or better yet, milk energy per cow has marked impacts on GHG emissions per unit milk. Additionally, if the culling rate is equalized to that in CA, numbers of young developing heifers would need to approximately double in N.Z., increasing the associated GHG emissions by about 12% for the herd with the same milk production. If all of the above - productivity, weight, manure, etc., factors are equalized across systems, the total CO<sub>2</sub>eq/milk are about equal, but from somewhat different sources, a 14% lower carbon dioxide cost in N.Z. is largely offset by a larger nitrous oxide emission. The pasture systems, at least in the N.Z., clover-ryegrass swards contain about 70% more nitrogen than is required, which results in more nitrous oxide losses through manure, legume fixation, crop residue and leached N sources

An additional factor not considered, is the number of calves available to produce beef from the dairy herds. The numbers will be considerably greater, with fewer cull cows from the N.Z. herd. Lower replacement rates leave more calves to produce meat without "maternal maintenance" requirements and concomitant GHG emissions. It is clear that these systems each have advantages and disadvantages.

Previous exercises (Johnson et al., 2001) with the cow-calf phase model showed emission responsiveness to modified herd characteristics or management criteria. Changes of 10% in calving or calf mortality rates have little effect on herd emissions but nearly linear effects of 8 to 12% on GHG emission per gain of the cow-calf phase. Changing the culling or cow replacement rate from 17 to 27% increased total herd CO<sub>2</sub>eq by about 3%, but gave a somewhat unexpected result of decreasing the cow-calf phase CO<sub>2</sub>eq/gain by 9%. Thus, an increased rate of slaughter of mature cows improves the emissions per product (culls + calves) ratio. With a 20% heavier mature cow size there was an increase of about 15% in each of the GHG, but when these emissions were expressed on a per kg gain basis there was a 2% reduction in GHG emissions. From an economic standpoint, increasing cow weights in this scenario improved profitability. Feed cost will probably determine whether the large cow scenario is profitable.

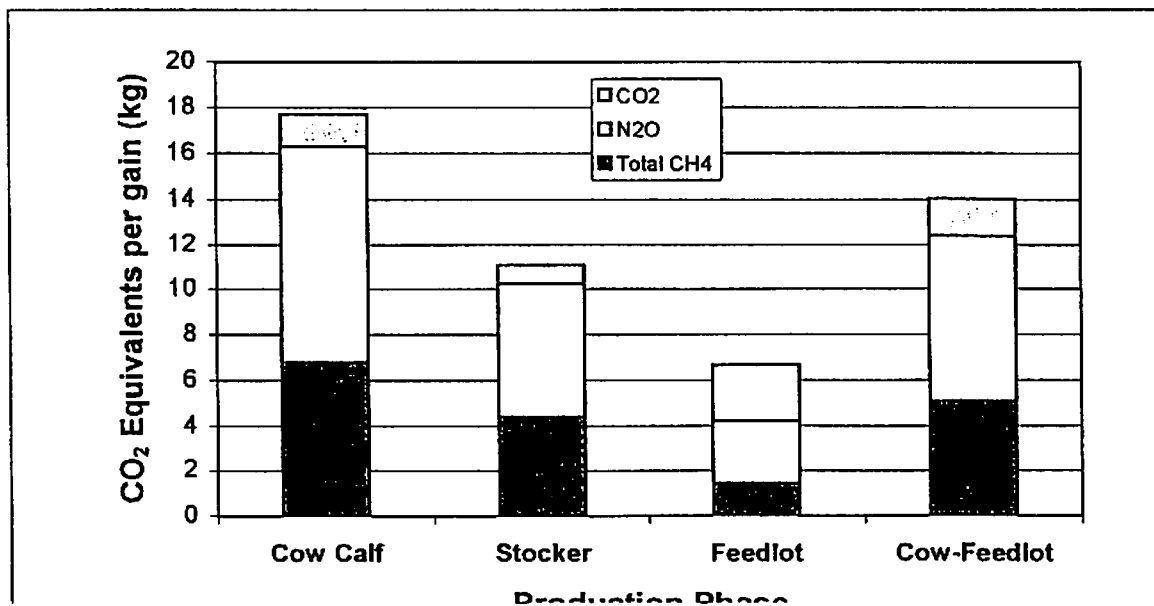
Approximately 76% of the total GHG emissions result from the cow-calf phase of beef production; 11% from the stocker and 13% from the feedlot phases. Presented as CO<sub>2</sub>eq/wt gain during each phase, the feedlot phase becomes the most efficient and produces only 60% as much CO<sub>2</sub>eq as the stocker phase and approximately one-third that of the cow-calf phase (Figure 1). Large emissions by the cow-calf phase reflect the greater proportion of feed used for maintenance. Lower feedlot phase emissions per gain reflect the opposite, high rates of gain and low proportions of feed for maintenance as well as the much lower methane emissions per unit of feed from cattle fed these 92% concentrate diets. Emissions from CO<sub>2</sub> and N<sub>2</sub>O become dominant and about equal for the feedlot phase of U.S. beef production.

A scenario was examined in which all of the weaned beef calves went directly to the feedlot, bypassing the stocker phase. Compared to the conventional cow through feedlot system, where only 18% went directly to the feedlot, the cattle are in the system 80 less days and produce just slightly more gain. The total number of ha required is reduced by about 13%, with little effect on total fuel and fertilizer use. As would be expected, these cattle emitted less CH<sub>4</sub> per unit gain, while N<sub>2</sub>O and CO<sub>2</sub> emissions were similar to the baseline scenario. Overall the total CO<sub>2</sub>eq were 8% less than the baseline. Of the mitigation strategies tested, delivering the calves directly to the feedlot from an intensive grazing (IG) cow-calf system was indicated to be the most profitable. The combination of the reduced CO<sub>2</sub>eq and increased profitability made this the mitigation strategy of choice.

Best management practices (BMP) for pasture or rangeland (Follet, et al., 2001) and/or cropland (Lal, et al., 1998) used in, or to produce feedstuffs for livestock operations present significant potentials to offset GHG emissions with increased soil-C sequestrations. Land use by the U.S. beef systems that we simulated, vary from 1.2 to 7.5 ha per cow unit (Table 4). Average C-sequestrations resulting from BMP's applied to these hectares suggest offsets ranging from 32 to 60% of the beef-herd CO<sub>2</sub>eq emissions (assuming no change in ha use per herd or other input requirements). Recent measurements by colleagues (Conant et al., 2001, unpublished) support annual C-sequestrations of approximately 0.4 Mg/ha in IG pasture in the southeastern U.S., although such increases in soil-C are not likely in areas with less than moderate rainfall. Other factors that must be considered are yield per ha or fertilizer inputs. A simulation of likely yield increases (+50%), fertilizer inputs (+20%), forage composition changes, and animal responses to intensive rotational grazing in the U.S., for example, would increase N<sub>2</sub>O, decrease CH<sub>4</sub> and total CO<sub>2</sub>eq emissions/gain slightly, offset 13 to 17% of emissions by soil-C increases, and decrease net GHG/gain by 14 to 20%. In any case, these projections of C-sequestration should be viewed as 'ballpark' because of the highly variable and difficult to measure productivity, animal harvest efficiency, and nutritive value of pasture-range. Additionally, long term IG and fertilization of pastures can yield C-sequestration losses, as reported recently by Lambert et al. (2000) following an 18-yr study in New Zealand.

Table 4. An estimate of annual land use and C sequestration potential of U.S. beef production systems (100-cow herd basis).

Items	Location in U.S.					Mean	
	AL	TX	UT	VA	WI		
<b>Land Use, ha/herd:</b>							
Managed pasture	143	102	129	104	94	114	
Rangeland	0	239	587	0	0	165	
Hay crops	13.1	22.3	21.0	15.2	20.6	18.5	
Grain crops	13.7	42.7	6.8	12.4	7.3	16.3	
Total, ha/herd	170	406	745	132	122	315	
<b>C-sequestration:</b>							
	t/ha	t carbon/herd					
BMP on pasture	0.4	57	41	52	42	38	46
BMP on range	0.0	0	12	29	0	0	8.2
	5						
BMP on hay crop	0.2	2.6	4.5	4.2	3.0	4.1	3.7
BMP on grain crop	0.8	11	34	5.4	9.9	5.8	13
Total C-sequestration		71	92	91	55	48	71
C-sequestration CO <sub>2</sub> eq		259	336	332	201	176	260
CO <sub>2</sub> eq emissions/herd		605	638	555	554	548	580
C-seq offset potential, %		43	53	60	36	32	45



*Figure 1. Relative source strengths of CO<sub>2</sub>eq by beef production phase.*

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## CO2 Production for dairy systems

	CA		WI		US		
	CO2 Equival.	Percent GHG/Net CO2 Equival.	CO2 Equiva	Percent GHG/Net CO2 Equival.	Mean	SD	
CO2 Production							
CO2/herd, 103 kg	296		407		351	78	
CO2/head, 103 kg	1.77		2.26		2.02	0.34	
CO2/milk, g/kg	329	26	567	40	448	168	
CO2/milksolids, kg	4.62		8.34		6.48	2.63	
CO2, 103 kg/ha	2.89		2.48		2.68	0.29	
CO2 Sources, 103 kg		% of total		% of total	Mean	SD	% of total
Fertilizer including lime	48.2		31.4		39.8	11.9	
Fuel	35.2		70.7		53.0	25.2	
Insecticide/herbicide	3.9		9.9		6.9	4.2	
Irrigation	33.5		0.0		16.7	23.7	
Machinery - Embodied	68.4		180.0		124.2	78.9	
Total cropping	189.2	64.0	292.1	71.8	240.6	72.8	68.5
Fuel - milking equipment	19.0		37.2		28.1	12.8	
Fuel - feed processing	22.4		19.0		20.7	2.4	
Fuel - transportation feed or animals	24.6		4.4		14.5	14.3	
Total fuel for farm operation	66.0	22.3	60.6	14.9	63.3	3.8	18.0
Embodied equipment	25.0		38.4		31.7	9.5	
Embodied buildings	15.5		15.5		15.5	0.0	
Embodied fences	0.03		0.04		0.03	0.01	
Total embodied farm energy excl. cropping	40.5	13.7	53.9	13.3	47.2	9.5	13.4
Total CO2 sources	296		407		351	78	