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Life Cycle Assessment of Rendering and Rendered Products

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Executive Summary

In this report a limited life cycle assessment of rendering and rendered products is developed and compared to two alternatives: composting as a method of handling meat byproducts and soy oil and meal as alternative products with similar attributes. Two environmental impacts are considered in each comparison: fossil fuel consumption and greenhouse gas emissions.

If a direct comparison is made between rendering and composting the same quantity of meat byproducts, rendering requires the consumption of about 10 times as much fossil energy, but composting emits at least 10 times more greenhouse gas. In a consequential assessment, which is generally considered to be more valid, the difference in fossil energy use is reduced, but the large advantage of rendering with respect to greenhouse gas emissions persists.

To compare the products of rendering to soy oil and meal, a basis of comparison must be chosen because the chemical composition and relative amounts of fat and protein produced by the two methods are not the same. If the comparison is made on the basis of equal economic value of the products, the production of soy oil and meal consumes about 60% as much fossil energy as the production of rendered fat and protein meal, and the two processes emit virtually equal quantities of greenhouse gas.

The soybean industry claims that soy products contain sequestered carbon dioxide because soybean plants absorb CO_2 from the atmosphere. Application of a credit for sequestered CO_2 appears to give soy products an advantage over rendered products with respect to GHG emissions. But the same credit can be claimed for rendered fat and protein meal if they are traced back to the growth of grain for animal feed. To retain the credit all GHG emissions resulting from feed growth and preparation and from animal growth and processing must be allocated to the meat produced for human consumption or to other meat byproducts that are not rendered. If rendered products are not held responsible for any of the GHG emissions associated with meat production, <u>and</u> the carbon in rendered products is credited as sequestered CO_2 since it originated as atmospheric CO_2 taken up by grain plants, then the net GHG emission associated with rendered products is negative. It is also essentially equal to the net GHG emission associated with soy products that have the same economic value.

If rendered and soy products are compared on the basis of equal metabolizable energy rather than equal economic value, approximately 50% more soy oil and meal must be produced. Thus comparing on the basis of metabolizable energy increases the fossil fuel consumed to make soy products to about 85% of that consumed to make an equal amount of rendered products. Also on this basis producing soy oil and meal emits 50% more greenhouse gas than producing an equal amount of rendered products. But using this basis also increases the CO_2 sequestration credit of soy products by 50%. Therefore, if metabolizable energy is used as a basis of comparison and a sequestration credit is allowed for both rendered and soy products, soy products are preferable over rendered products with respect to GHG emissions.

Background and Organization of this Report

The rendering industry has come under pressure from various sources to prove that rendering is a green process compared to alternative technologies. Raw material providers compare rendering to other methods of handling animal byproducts, such as composting. Customers who purchase rendered products compare them to alternative sources of fats, oils, and protein meals.

In previous work, the Principal Investigator developed a spreadsheet to calculate the carbon footprint of rendering operations. The carbon footprint tool was converted into an interactive form and is available for use by members of the National Renderers Association on the web site of the Fats and Proteins Research Foundation. An article on the carbon footprint calculator was written, peer reviewed, and published in the Journal of Industrial Ecology (1). The experts who critiqued the original version of the article correctly pointed out that the data were inadequate to support a complete life cycle assessment (LCA), which is the modern standard for comparing environmental impacts of competing processes and products.

In this report a more complete life cycle assessment of rendering operations is developed. The objective is to compare rendering to specific alternatives that are well known and mentioned frequently. Raw material providers often cite composting as a potentially preferable way of handling meat byproducts. Some rendered product customers consider soy oil and meal to be greener than their rendered counterparts. The comparison in this LCA is focused on two environmental impacts that are subjects of concern – fossil fuel consumption and greenhouse gas (GHG) emissions.

The first section of the report explains basic concepts and requirements of life cycle assessment. Diagrams and tables are then presented for five processes to show inputs of raw materials and fossil fuel and outputs of products and greenhouse gases. Data are shown for rendering, composting, production of soy oil and meal, meat production, and production of nitrogen fertilizer. The latter two are needed to put the comparison of rendering and its primary alternatives on an equivalent basis. The summary data presented on each process are supported by a more complete explanation and analysis in an appendix of the report. Spreadsheets that show even more detailed calculations are available upon request from the Principal Investigator.

Following the input/output tables of the five processes is a comparison of rendering to composting and rendered products to soy products. The comparison of rendered and soy products is direct. The comparison of rendering to composting is presented directly and in the form of a consequential life cycle assessment. A statement of conclusions completes the main body of the report. Cited references and an additional bibliography follow the appendices.

Basic Concepts of Life Cycle Assessment

The concept of life cycle assessment has developed over the last forty years as an alternative to methods of decision making and optimization that are based solely on economics. In a recent paper Guinée et al. (2) analyze the rationale behind the use of LCAs, a brief history on the development of methods and standards, and examples of the use of LCAs in decision making.

According to ISO 14040 and ISO 14044 (3, 4) an effective life cycle assessment must include certain essential, interdependent components. The first is a clear statement of objectives. The functional unit, or basis on which alternatives are compared, must be defined explicitly. For example, an LCA to compare rendering operations to composting might be based on a functional unit of one metric tonne (1000 kg) of animal byproducts of a certain composition. To compare rendering to other sources of fat and protein the functional unit could be a specified mass and composition of each product, or the functional unit could be any combination of fat and protein that delivers a specified quantity of metabolizable energy, or any combination of fat and protein that has a specified market value.

The functional unit selected for an LCA influences which alternatives are evaluated and the boundaries of the analysis. A cradle-to-grave analysis has the widest boundaries and is generally the most demanding LCA to conduct. For a rendering process, the cradle would go all the way back to the grain grown as feed for the production of animals whose byproducts enter rendering as raw material. The grave would extend to the ultimate conversion of rendered products into molecular constituents that are returned to the environment; e.g. carbon dioxide, water, nitrogen in some form, and ash. If more narrow boundaries are selected for an LCA, the rationale behind their use must be justified in a convincing manner, or the LCA will not be taken seriously.

Life cycle assessments that claim to compare alternative products or alternative processes must be constructed with boundaries, inputs, and outputs that are as nearly identical as possible. For example, it might seem reasonable to compare greenhouse gas emissions from a rendering plant with those from a composting operation that is fed an equivalent meat byproduct stream. But these two alternative methods of meat byproduct disposal do not produce the same product output. Rendering produces animal fats and proteins, and composting produces a soil amendment product. To develop a more valid LCA comparison, the boundaries of each alternative are usually expanded so that they produce the same result. For example, to the rendering alternative one could add a parallel process that produces a soil amendment agent comparable to compost. To the composting alternative one could add a parallel process that produces a vegetable oil and protein meal comparable to rendered products. Of course, this does not mean that a rendering company must go into the fertilizer business or that a composting facility must produce vegetable oils and proteins. The addition of parallel units is hypothetical to make the comparison valid on paper. The concept is known as a "consequential LCA" (5). The idea is that if meat byproducts are rendered instead of composted, someone, somewhere would have to produce a soil amendment product to replace the lost compost. Likewise, if meat byproducts were composted instead of rendered, someone, somewhere would build or expand a vegetable oil and meal process to replace the products from rendering that had been lost from the marketplace.

Yet another complication occurs if a process included in an LCA has more than one function or produces more than one product. When this occurs, decisions must be made about how to allocate resources consumed (e.g. energy) and impacts (e.g. pollutant emissions) among these functions and/or products. The issue of allocation and methods of handling this problem are a common and often controversial topic in the LCA literature (6-11).

The most labor-intensive part of an LCA is usually the collection and analysis of data that follows after the objectives, functional unit, and boundaries are defined. Quantities or flow rates of raw materials, utility streams, products, byproducts, wastes, and all other pertinent inputs and outputs must be determined, scaled to the functional unit, allocated among functions and co-products, and converted into a form that will allow quantitative impacts to be calculated. Impact categories are chosen based on the objective of the LCA, and data on these impacts must be included in the inventory. An LCA can be limited to one impact such as greenhouse gas emission, or it can include several, such as energy consumption, water consumption, BOD discharges, a specified measure of human health risk, etc. Data and rational estimates must be developed and presented to quantify each impact addressed in the LCA. Unsubstantiated estimates and claims are generally not acceptable. Assumptions must be formulated and stated clearly because they will be subject to challenge by the target audience of the LCA and by constituents who represent the alternatives that are deemed to be inferior.

The final phase of an LCA is interpretation. Results are analyzed and summarized and conclusions are stated. To the extent possible, a sensitivity analysis is presented, and confidence limits are placed on key data. Methods of developing, presenting, and interpreting LCA data are an ongoing subject of study, discussion, and debate (7, 12).

Input/Output Data on Rendering and other Pertinent Processes

A more detailed explanation and analysis of each process presented below can be found in the appendices that follow the main body of this report. GHG emissions are reported in terms of carbon dioxide equivalents (CO_2e), which account for the emission of three greenhouse gases – carbon dioxide, methane, and nitrous oxide. Conversion from actual methane and nitrous oxide emissions to CO_2e was based on the IPCC AR4 global warming potential of each gas (13). Carbon dioxide is assigned a value of 1, and over a 100 year time horizon the GWPs of CH_4 and NO_2 have been determined to be 25 and 298, respectively.

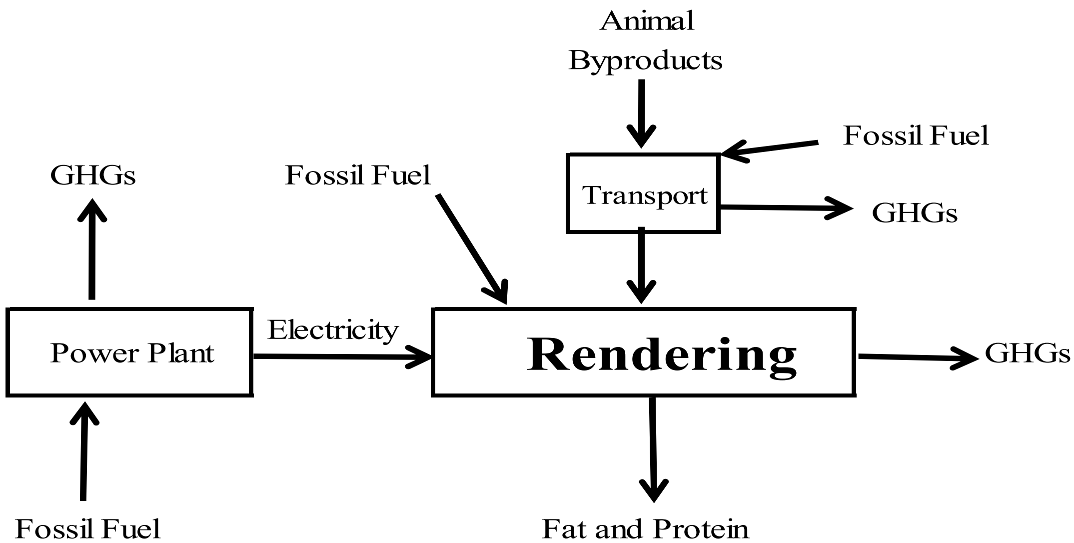
Rendering of Animal Byproducts

The diagram and data shown in Figure 1 are consistent with the carbon footprint for rendering operations that was published by Gooding in 2012 (1). Input/output data are scaled to a functional unit of 1000 kg of mixed raw materials entering the rendering process, which results in the production of 220 kg of fat and 200 kg of protein product on average. Fossil fuel use and GHG emissions attributable to the production of electricity used in the plant are included in accordance with generally accepted protocols (14, 15). Inclusion of fuel use and GHG emissions associated with transportation of the raw materials to the rendering plant assumes that transportation occurs in vehicles owned or controlled by the rendering company. Fuel use and emissions that result from workers commuting to and from the plant, from other company personnel travelling off-site, and from transportation of products are not included.

The fossil fuel input and GHG emission output streams connected directly to the rendering process in Figure 1 result from burning of purchased fossil fuels, burning of fat produced (emissions only because fat is not a fossil fuel), wastewater treatment, and operation of vehicles on site.

Other data shown in Figure 1 will be important to comparisons made later in this report. The metabolizable energy contents of rendered fat and protein product [37 MJ/kg and 12 MJ/kg, respectively] were estimated from rounded Atwater values published in an FAO food and nutrition paper (16). These values result in ME estimates that are about 10% higher than those found in Meeker and Hamilton's overview in Essential Rendering (17). Estimates of economic value [$0.80/kg of rendered fat and $0.50/kg of protein product] were based on recent data reported by Swisher (18). The mass of carbon dioxide equivalents sequestered in rendered products leaving the process is based on the average carbon content of fat and protein produced in a plant that processes a mix of raw materials [see Tables 1 and 2 in Gooding's carbon footprint analysis (1)].

Figure 1. Input/Output data for a typical rendering process.



Animal byproducts in	1,000 kg		
Products out		metabolizable energy (ME)	economic value
Fat product	200 kg	7,400 MJ	$160
Protein product	220 kg	2,640 MJ	$110
Total	420 kg	10,040 MJ	$270
Fossil fuel used			
byproduct transport	230 MJ		
power plant	580 MJ		
rendering	1,770 MJ		
Total fossil fuel use	2,600 MJ		
Greenhouse gas out			
transport	18 kg CO_2e		
power plant	44 kg CO_2e		
rendering	163 kg CO_2e		
Total GHG emissions	220 kg CO_2e		
sequestered CO_2 in products leaving the rendering process	-750 kg CO_2		

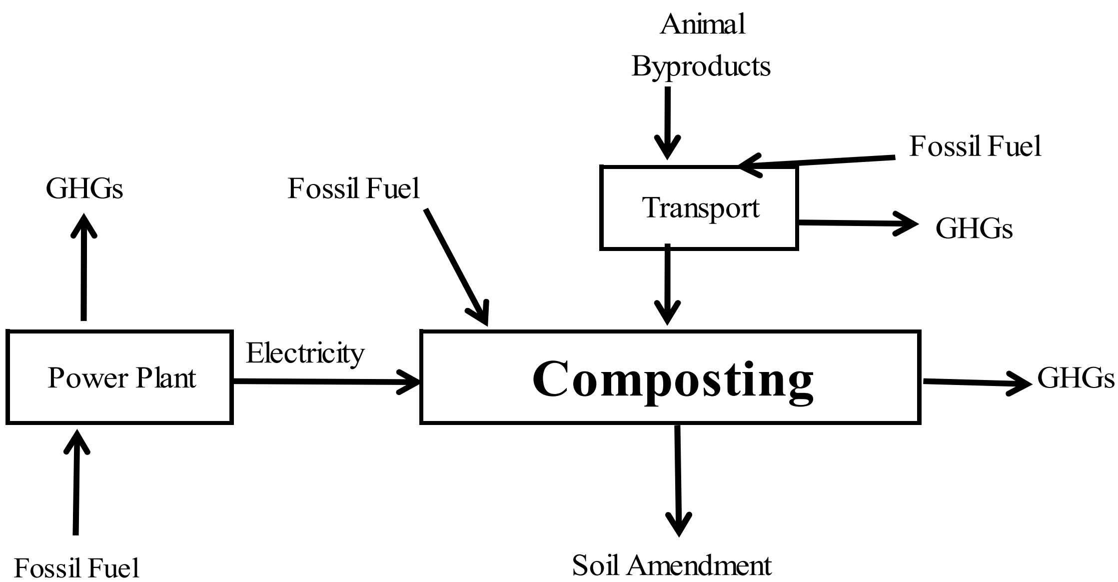
Composting of Animal Byproducts

Figure 2 is an input/output diagram for composting 1000 kg of animal byproducts of the same composition as the byproducts rendered in Figure 1. In actuality meat byproducts cannot be composted unless they are mixed with other materials such as manure and straw. The mass of animal byproducts in a compost pile (not including the manure) is usually 5 to 10% of the total mass. The results shown in Figure 2 are based on two large-scale studies conducted in Western Canada (19, 20) over several months, one with adult cattle mortalities and the other with calf mortalities. Each study compared side-by-side composting in two 2m by 2m by 30 m windrows that were identical except for the presence or absence of animal byproducts. Gaseous emissions were measured periodically over the course of the experiment, and chemical analyses were conducted on each material originally added to each compost windrow and on the final compost at several locations in each windrow. In each study the measured emissions and final compost composition obtained from the windrow without byproducts was then compared to the emissions and compost composition from the windrow with byproducts to deduce the effects that were attributable to animal byproducts. The results were then scaled to a functional unit of 1000 kg of animal byproducts composted, and Figure 2 is the result.

In Figure 2 it is assumed that fossil fuel use and greenhouse gas emissions attributed to raw material transportation are the same for composting and rendering. The data on raw material transportation for a rendering plant were obtained primarily from independent renderers that collect raw materials from many sources. If a large-scale composting facility were set up to provide a similar service, transportation fuel use and GHG emissions should be essentially the same as those for transporting animal byproducts to a rendering plant. Because composting of animal byproducts requires roughly ten times more manure than meat byproducts, another likely application of composting is to handle mortalities on an individual farm or at a feed lot operation. For this type of application, transportation of the raw materials would be negligible. The Canadian composting studies reported no data on the use of fuel or electricity. Farm equipment was used to assemble the windrows and to turn the contents of each windrow twice over the duration of the experiment, but fuel use and GHG emissions associated with these activities were negligible compared to fuel burning to produce steam at a rendering plant. Likewise electricity for lighting and operation of small equipment at a composting facility should be minimal so power plant fuel use and GHG emissions are shown as zero in Figure 2.

The two Canadian composting studies yielded somewhat different emissions and final compost compositions. Mass balances on carbon and nitrogen were not completely consistent in either study when initial windrow contents were compared to measured emissions and final compost composition. These discrepancies are not surprising given the physical size (120 m^3) and mass (over 100,000 kg) of each windrow and the duration of the studies (~300 days each). In the observations summarized below CM refers to data from a compost windrow that had bovine mortalities present, and CK refers to control data from a compost windrow that was identical except for the absence of bovine mortalities.

Figure 2. Input/Output data for composting of animal byproducts.



Animal byproducts in	1,000 kg	
Products out	cow study	calf study
Total nitrogen	11 kg	19 kg
NH_4^+	3.2 kg	1.6 kg
NO3-	0.4 kg	6.0 kg

Fossil fuel used		
byproduct transport	230 MJ	same as rendering
power plant	0 MJ	negligible
composting	0 MJ	negligible
Total fossil fuel use	230 MJ	

Greenhouse gas out	cow study	calf study
transport	18 kg CO_2e	18 kg CO_2e
power plant	0 kg CO_2e	0 kg CO_2e
composting	2,600 kg CO_2e	3,900 kg CO_2e
Total GHG emissions	2,600 kg CO_2e	3,900 kg CO_2e

In the study conducted with adult cattle mortalities (19):

- The CM windrows had significantly higher emissions of CO_2, CH_4, and N_20 than the CK windrows.
- Comparing CM and CK emission data and the initial mass of C calculated to be in the cattle composted indicated that 77% of the C in the cattle mortalities was emitted as CO_2 and 4% as CH_4.
- Comparing residual CM and CK compost data indicated that 23% of C in the cattle mortalities was retained or 77% was emitted, which is reasonably close to the total of 81% C loss indicated by the emission data.
- Comparing CM and CK emission data and the initial mass of N calculated to be in the cattle composted indicated that 6% of the N in cattle mortalities was emitted as N_2O.
- Comparing residual CM and CK compost data indicated that 41% of N in the cattle mortalities was retained or 59% was lost. The additional N loss could have been in the form of NH_3 emissions, which were not measured.

In the study conducted with calf mortalities (20):

- The CM windrows had significantly higher emissions of CO_2, CH_4, and N_20 than the CK windrows.
- Comparing CM and CK emission data and the initial mass of C calculated to be in the cattle composted indicated that 45% of the C in the cattle mortalities was emitted as CO_2 and 19% as CH_4.
- Comparing residual CM and CK compost data indicated that 18% of C in the cattle mortalities was retained or 82% was emitted, which is higher than the total of 64% C loss indicated by the emission data.
- Comparing CM and CK emission data and the initial mass of N calculated to be in the cattle composted indicated that 9% of the N in cattle mortalities was emitted as N_2O.
- Comparing residual CM and CK compost data indicated that 61% of N in the cattle mortalities was retained or 39% was lost. The additional N loss could have been in the form of NH_3 emissions, which were not measured.

For comparison to rendering, the measured emission data from the two Canadian composting studies were converted to carbon dioxide equivalents (CO_2e) and scaled to a basis of 1000 kg of animal byproducts. The results are shown at the bottom of Figure 2 as composting emissions. The adult cattle (cow) study indicated that GHG emissions from composting animal byproducts are almost 12 times higher than rendering the same mass of animal byproducts. The calf study indicated that composting emits more than 17 times as much greenhouse gas.
In the study with adult cattle mortalities present total nitrogen (TN) content of the final compost was 25% higher that the control CK treatment, ammonium nitrogen (NH_4^+) content was 27 times higher, and C/N ratio was lower. All of these differences presumably resulted from the protein content of the carcasses. Inclusion of carcasses did not have a significant effect at the 0.05 probability level on water content, total carbon (TC), nitrates (NO_3^-), or nitrites (NO_2^-) of the

final compost. In other words, it is not possible to say with 90% confidence that the final CM and CK levels of these variables were different.
The results from the study that composted calf mortalities were somewhat different. TN content of the final compost was not significantly higher in the CM treatment than in the control CK treatment, but NH_4^+ and NO_3^- contents were each 6 times higher with calf mortalities present, and C/N ratio was lower. Inclusion of carcasses did not have a significant effect on water content, TC, or NO_2^- content of the final compost at the 0.05 probability level.
Compost can be used as a soil amendment, and various sources claim various benefits and characteristics of the material [see, for example, AAPFCO Soil Amendment/Compost Uniform Product Claims (21)]. Based on the Canadian studies, however, the only specific differences between the characteristics of the final CM and CK compost that were noted to be significant were TN, NH_4^+ and NO_3^- levels, with NO_3^- level being significantly different in the calf study only. Thus Figure 2 shows the product output from co-composting 1000 kg animal byproducts with manure and straw as opposed to composting manure and straw only. Recent USDA data (22) indicate that the economic value of various forms of nitrogen fertilizer is about $1/kg of TN. This means that co-composting 1000 kg of animal byproducts with 10,000 to 20,000 kg of manure generates only 4% to 7% as much economic value as rendering the animal byproducts and composting the manure alone [$11 to $19 added to the value of the compost vs. $270 for the fat and protein meal that are obtained from rendering 1000 kg of animal byproducts].

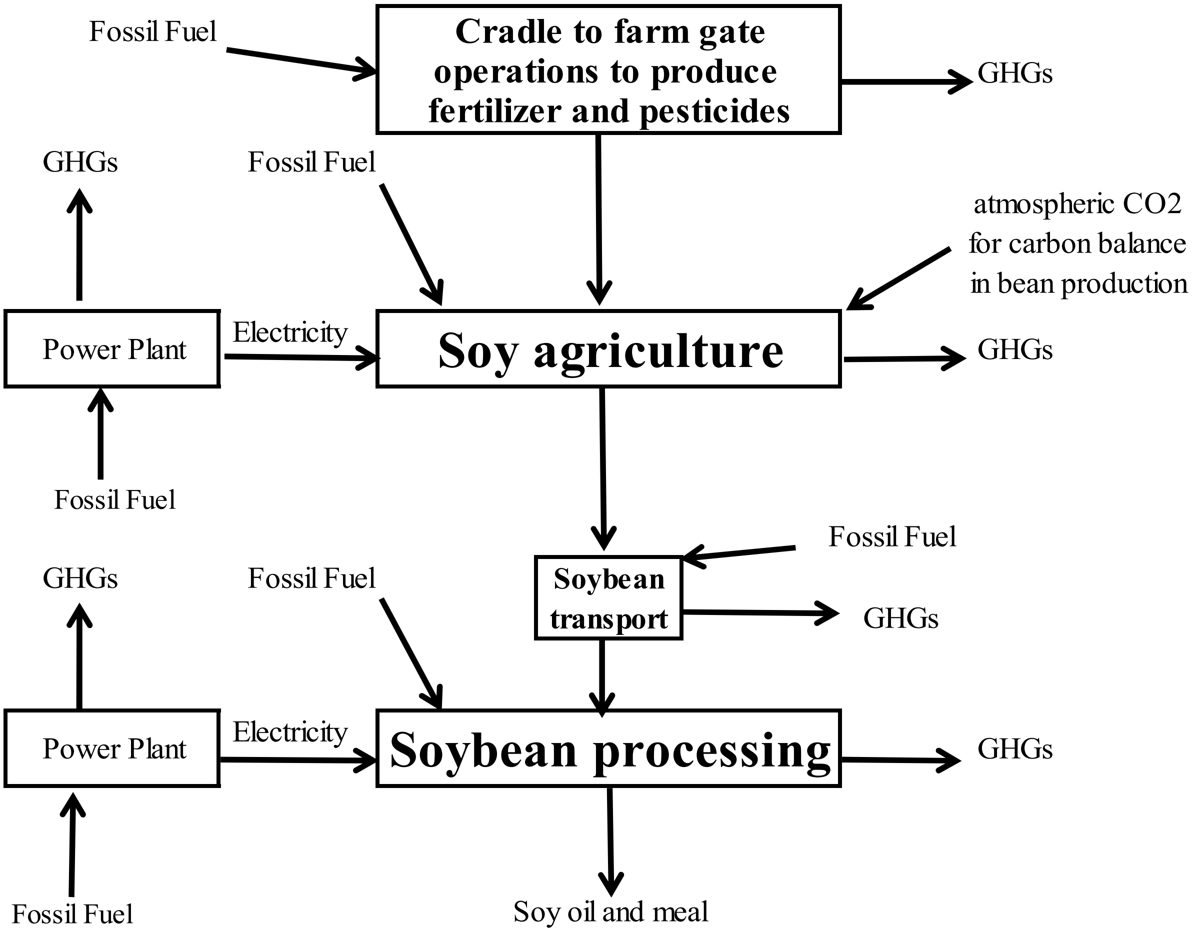
Production of Soybean Oil and Meal
Figure 3 is a cradle-to-gate diagram for fossil fuel use and greenhouse gas emission associated with the production of soybean oil and meal. Data in the diagram were derived primarily from a report commissioned by the United Soybean Board (USB) and developed by Omni Tech International (23). The analysis started with fertilizer and pesticides that were produced for soybean agriculture. The beans were grown and then transported to a processing plant where they were converted into soy oil and soy meal.

On average, soy meal and soy oil are produced from beans in a mass ratio of roughly 4:1 whereas rendered protein meal and fat are produced in a mass ratio closer to 1:1. At least two logical methods can be used to put these product output streams on an equivalent basis despite the different protein to fat ratios and molecular compositions. The data in Figure 3 were scaled to result in a mass of soy oil and meal products that have the same economic value as the products obtained from rendering 1000 kg of animal byproducts as shown in Figure 2. The value of each of these commodities varies with time so recent market trends (18, 24) were used to establish reasonable estimates of the relative values. For this analysis rendered fat was estimated to be worth $0.80/kg and soy oil to be worth $0.94/kg. Soy meal and rendered MBM were both valued at $0.50/kg. These economic estimates mean that 462 kg of combined soy products (90 kg of soy oil and 372 kg of soy meal) must be produced to provide the same economic value as 420 kg of products (200 kg fat and 220 kg of protein meal) from a rendering plant that processes 1000 kg of raw material with the characteristics used to develop Figure 1.
An alternative method of putting a rendering plant and a soybean operation on the same basis is to specify that each must produce the same amount of metabolizable energy (ME) for application in animal feeds. Rendered fat and soy oil have approximately the same ME value of 37 MJ/kg (16), but MBM has a higher ME value than soy meal. MBM typically contains 50% crude protein and 10% fat. Soy meal typically contains 48% crude protein and 10% fiber, which has a

substantially lower ME than fat. Thus it takes 1.3 kg of soy meal to provide the same ME as 1.0 kg of MBM. The overall result is that the process shown in Figure 3 would have to be scaled up by a factor of 1.5 to be equivalent to the rendering operation in Figure 2 on the basis of metabolizable energy production, which means that the fossil fuel use and GHG emission associated with soy products would be 50% higher than those shown in Figure 3.

On the basis shown in Figure 3 the production of soy oil and meal requires the consumption of 1500 MJ of fossil fuel, which is 42% less than the fossil energy required to produce an equivalent amount of rendered products. If metabolizable energy of the products is used as the basis of comparison rather than economic value, the fossil fuel burden of soy products goes up to 2250 MJ, which is still 13% less than the fossil fuel required to produce the equivalent amount of rendered products.

Figure 3. Input/Output data for growth of soybeans and processing to soy oil and meal.



Products out		metabolizable energy (ME)	economic value
Soy oil	90 kg	3,330 MJ	$85
Soy meal	372 kg	3,420 MJ	$186
Total	462 kg	6,750 MJ	$270

Fossil fuel used		Greenhouse gas out	
fertilizer/pesticide	296 MJ	fertilizer/pesticide	61 kg CO_2e
power for agriculture	24 MJ	power for agriculture	2 kg CO_2e
soybean agriculture	351 MJ	sequestration in beans	-735 kg CO_2
soybean transport	150 MJ	agriculture emissions	74 kg CO_2e
power for processing	94 MJ	soybean transport	12 kg CO_2e
soybean processing	561 MJ	power for processing	17 kg CO_2e
		soybean processing	38 kg CO_2e
Total fossil fuel use	1,500 MJ	Total GHG emissions	210 kg CO_2e
		Net with sequestration	-530 kg CO_2e

The United Soybean Board report (23) divides the production of soy oil and meal into two distinct steps – soybean agriculture and soybean processing. Greenhouse gas emissions are divided further into three components in agriculture. The manufacture of the fertilizer and pesticides typically used to grow soybeans results in the emission of 61 kg CO_2e for the scale of operation used as the basis of Figure 3. Generation of electricity for soybean agriculture results in 2 kg CO_2e, and direct emissions on the farm contribute another 74 kg CO_2e. The total for agriculture is 137 kg CO_2e. Processing of the beans into oil and meal results in the emission of another 67 kg CO_2e, which includes12 for transport from the farm to the processing plant, 17 for generation of electricity used at the processing plant, and 38 kg CO_2e in direct emissions during processing. The total GHG emitted to produce the soy oil and meal is 210 kg CO_2e when rounded to two significant figures. <u>But</u> the USB report applies a credit for 735 kg of CO_2 that is sequestered in the beans when they are grown. This credit is passed on to the soy oil and meal. In other words, all of the carbon that leaves the processing plant in soy oil and meal was derived from the conversion of atmospheric CO_2 into other carbon-containing molecules when the soybeans were grown. This means that the overall effect of producing soy oil and meal with an economic value of $270 is the removal of 530 CO_2 from the atmosphere.

If metabolizable energy is used as the basis for establishing equivalence between rendered fat and meal and soy oil and meal, 50% more beans must be produced. This increases all of the GHG emissions by 50% compared to the values shown in Figure 3, but it also increases the sequestration credit by 50%. In other words, the more soy beans one grows the better with respect to reducing greenhouse gases in the atmosphere, at least in a cradle-to-gate analysis that does not consider the fate of the beans.

The greenhouse gas emission credit for CO_2 sequestration claimed in the USB report certainly implies that soy oil and meal are "greener" than the products of rendering. To determine whether this apparent advantage is real, new questions must be considered:

- What is the source of the carbon that leaves a rendering plant in fat and protein meal?
- Is it reasonable to claim a CO_2 sequestration credit for the products of rendering?
- If the boundaries of the life cycle assessment on rendering are expanded to take into account the source of the raw materials, will this introduce additional burdens with respect to fossil energy consumption and greenhouse gas emissions?

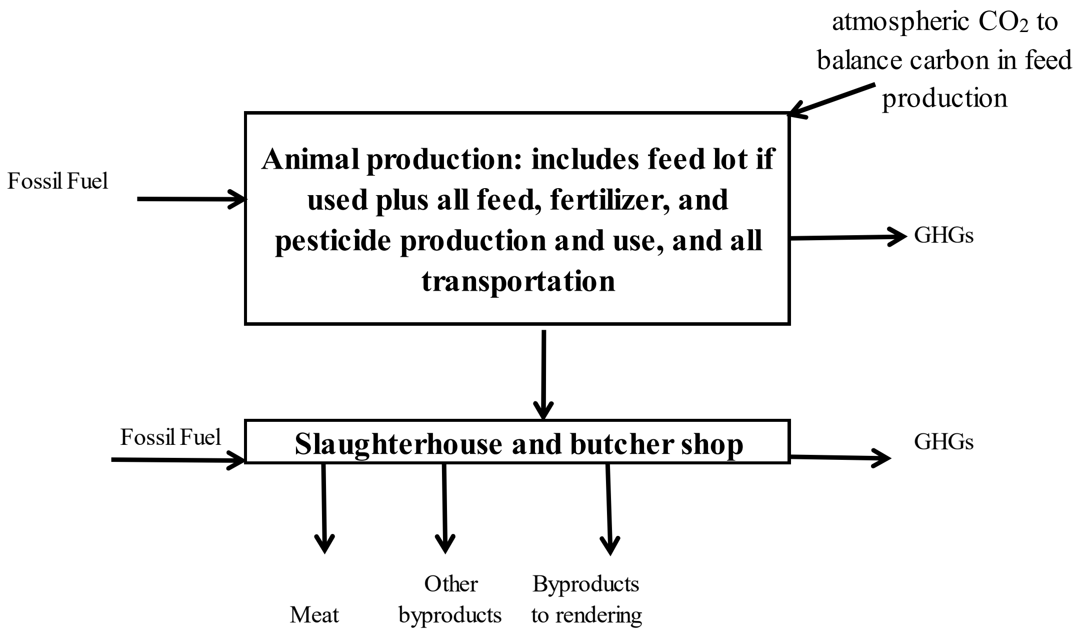
These questions are addressed in the next section.

Meat Production: The Cradle-to-Gate Source of Rendering Plant Raw Materials
Figure 4 is a simplified input/output diagram for meat production divided into two parts – animal production and slaughtering operations. Animal production actually involves several steps that are combined in Figure 4 for simplicity. Feed is required to produce and maintain livestock. Fertilizer and pesticides are required to grow the grain used to produce animal feeds. Fertilizer and pesticide production are industrial operations; while feed production and animal production are agricultural operations. Each of these involves transportation of raw materials and/or finished products.

Three columns of data are provided in Figure 4 - one each for the production of beef, poultry, or swine (8, 25-27). With respect to fossil fuel consumption and greenhouse gas emissions, beef production has a much larger impact than pork production, which has a larger impact than poultry production. Animal production is far more significant than slaughterhouse and butcher shop operations in each case. Further explanation of the data in each column of Figure 4 is provided in Appendix D.
Each column in Figure 4 is scaled to facilitate comparison with Figure 1 in that 1000 kg of animal byproducts are produced and sent to rendering. No single column of data from Figure 4 can be combined with Figure 1 to produce a perfect cradle-to-rendering-gate analysis because the data in Figure 1 are based on a rendering plant that processes a mix of raw materials. So the match is not perfect, but comparison of the two tables shows clearly that if rendering is burdened with a significant fraction of the environmental impacts of meat production, rendered products will suffer in comparison to soy oil and meal. For example, comparison of fuel consumption and GHG emission data for beef production in Figure 4 reveals that each is roughly two orders of magnitude larger than the impact of rendering the beef byproducts (data shown in Figure 1).

When a process produces more than one product, the impacts addressed in a life cycle assessment must be allocated among the products. The most appropriate basis of allocation is a topic of continuing debate, but relative mass and economic value are the most common choices (6-11). The "Products out" section of Figure 4 shows the relative masses of meat, byproducts rendered, and other byproducts for beef, poultry, and pork. The portion of live animal weight sent to rendering ranges from 26% for beef and pork to 37% for poultry. Use of mass allocation would add significantly to the fossil fuel consumption and GHG emission burdens of rendering the byproducts from any of these animals. Allocation on the basis of relative economic value is arguably a more logical approach because the economic value of produced goods and services is the driving force behind business activity. Compared to the economic value of beef, pork, and poultry sold for human consumption, the value of the meat byproducts sent to rendering is near zero. Thus it can be argued that all of the resource consumption and environmental consequences of meat production should be allocated to the primary meat product and to other byproducts that have positive economic value, and none should be allocated to byproducts that are sent to rendering.

Figure 4. Input/Output data for meat production.



	Beef	Poultry	Swine
Products out [1]			
Meat	1,300 kg	1,400 kg	1,300 kg
Other byproducts	1,500 kg	300 kg	1,500 kg
Byproducts to rendering	1,000 kg	1,000 kg	1,000 kg
Total	3,800 kg	2,700 kg	3,800 kg
Fossil fuel used [2,3,4,5]			
animal production	145,000 MJ	32,000 MJ	53,000 MJ
slaughterhouse	8,000 MJ	5,000 MJ	8,000 MJ
Total	150,000 MJ	37,000 MJ	61,000 MJ
Greenhouse gas out			
animal production	56,000 kg CO_2e	8,000 kg CO_2e	13,000 kg CO_2e
slaughterhouse	1,000 kg CO_2e	1,000 kg CO_2e	1,000 kg CO_2e
Total emissions	57,000 kg CO_2e	9,000 kg CO_2e	14,000 kg CO_2e
sequestered CO_2 in animal byproducts to rendering process [6]	-930 kg CO_2	-520 kg CO_2	-930 kg CO_2

Notes:
1. For beef and poultry, the relative mass of meat, byproducts to rendering, and other byproducts is based on Lopez et al. (28) with the fraction of byproducts to rendering increased slightly to account for rendering of fallen animals. Beef mass ratios are used for swine also, based on edible fraction data of de Vries and de Boer (8).
2. Beef fossil fuel use and GHG emissions are based on farm plus feedlot estimates in Pelletier et al. (25).
3. Poultry fossil fuel use and GHG emissions are based on mid-range estimates in de Vries and de Boer (8).
4. Swine fossil fuel use and GHG emissions are based on mid-range estimates in de Vries and de Boer (8).
5. Slaughterhouse fossil fuel use and GHG emissions are based on mid-range of estimates in Lopez et al. (27).
6. The mass of CO_2 sequestered in beef, poultry, and swine byproducts is based on Table 1 in Gooding (1).

The other important question that is answered in Figure 4 is the source of the carbon in animal byproducts and thus the source of the carbon in the products that leave a rendering plant. Clearly the source of this carbon is the feed consumed by the animals. All of this carbon is plant-based. Most comes from grain grown for the specific purpose of producing feed. Some comes from feed supplements, but those were derived from other plants (e.g., soy) or from the processed byproducts of animals that had been fed grain. Figure 4 illustrates the fact that all of the carbon in meat byproducts (and thus all of the carbon in the rendered fat and protein meal produced from these byproducts) can be traced back to carbon dioxide absorbed from the atmosphere when plants were grown. This conclusion justifies the use of a carbon sequestration credit for rendered products in the same way that a credit is claimed for soy oil and meal.

Production of Nitrogen Fertilizer

GHG emissions and fossil energy consumption associated with the production of nitrogen fertilizer must be included in this discussion because added nitrogen is the primary benefit of composting meat byproducts with other organic materials. The NREL life cycle inventory database (28) contains data on fossil fuel use and greenhouse gas emissions associated with the production of nitrogen fertilizer from natural gas. Calculations for the cradle-to-gate production of 1 kg TN (total nitrogen) results in the emission of 0.65 kg CO_2, 0.0044 kg N_2O, and 0.0015 kg CH_4, which translates into 2.0 kg of CO_2 equivalents in terms of global warming potential. Also application of data from the NREL database reveals that to produce 1 kg TN, 36 MJ of fossil energy is consumed.

Compost analyses from the two Canadian studies that were used as the basis of Figure 2 differed significantly, but on average these studies indicated that co-composting 1000 kg of meat byproducts adds 15 kg of TN to the compost produced. According to the NREL data, replacement of this 15 kg of TN by manufacturing nitrogen fertilizer in a conventional process would result in the consumption of 540 MJ of fossil fuel and the emission of 30. kg of CO_2e.

Comparison of Rendered Products to Soy Oil and Meal

Rendered fat and protein meal can be compared directly to soy oil and meal by examining the data presented in Figures 1 and 3 <u>if</u> two important (and probably controversial) stipulations are accepted. The essential stipulations for direct comparison: (1) carbon in the meat byproducts entering the rendering process represents sequestered CO_2, and (2) none of the negative environmental impacts that result from meat production is allocated to the animal byproducts that are rendered. The soy input/output diagram shown in Figure 3 is cradle-to-product gate. All of the fossil fuel consumed and greenhouse gases emitted during the growing and processing of soybeans are included in the analysis. A GHG credit for uptake and sequestration of carbon dioxide from the atmosphere by soybean plants is also included. In contrast the rendering input/output diagram in Figure 1 is gate-to-gate. To make a direct and favorable comparison, credit will be taken for the fact that the meat byproducts entering the rendering plant and thus the rendered products leaving the plant contain carbon that was derived from carbon dioxide sequestered by plants. The raw materials arriving at the entrance gate of the rendering plant will not be held responsible for any of the fossil fuel consumed or greenhouse gases emitted during meat production and processing. All negative environmental impacts of meat production are assigned to the primary product or to other byproducts that have significant economic value. Therefore the cradle-to-rendering plant entrance gate impact is zero.

Two alternative bases of comparison should also be considered when the data in Figures 1 and 3 are examined. The process in each figure produces triglycerides (fat or oil) and a protein-rich product, but the fatty product and the protein product in each case are not identical and they are not produced in the same mass ratio. Soy meal and soy oil are produced in a mass ratio of approximately 4:1 regardless of the source of the soy beans or the particular processing plant. The relative masses of fat and protein meal leaving a rendering plant depend on the characteristics of the raw material entering the plant. The data in Figure 1 show roughly equal masses of fat and protein meal leaving the rendering process, based on a mix of raw materials that reflects the annual average of raw materials rendered in North America.

To compare the unequal amounts of fat and protein produced some equivalence factor must be used. The data in Figures 1 and 3 can be compared on the basis that the total economic value of the products leaving each process is the same ($270 for the particular scale shown). On this basis production of soy-based products consumes 42% less fossil energy (1500 MJ vs. 2600 MJ) than production of an equivalent amount of rendered products. The total greenhouse gas emissions attributed to the two alternative processes are essentially equal (220 kg CO_2e for rendered products vs. 210 kg CO_2e for soy products). The sequestered CO_2 is also essentially the same (750 kg vs. 735 kg), so the net GHG emission is virtually identical for each process (-530 kg CO_2e). Thus on the basis of equivalent economic value of products, soy products and rendered products are both beneficial and equal with respect to greenhouse gas emissions.

If metabolizable energy is used as a basis of comparison instead of economic value of the products, the numbers in Figure 3 must all be multiplied by a factor of 1.5 to establish equivalence (10,040 MJ/6750 MJ = 1.5). When this is done, the fossil energy consumption of the soy products rises to 2250 MJ, and the advantage of soy products over rendered products is reduced to 13%. On the basis of equivalent metabolizable energy, the total GHG emissions associated with the soy products increases to 320 kg CO_2e and the CO_2 sequestration credit increases to 1100 kg, so the net result for soy products is -780 kg CO_2e versus -530 kg CO_2e for rendered products. So if metabolizable energy is used as the basis for equivalence, soy products are 50% more environmentally friendly than rendered products simply because more beans must be grown to provide the equivalent amount of products, and growing soybeans sequesters CO_2. How long the sequestration persists depends on the use of the soy oil and meal, but the outlet gate of this analysis is the product loading dock of the soy processing plant so the sequestration credit is valid.

Comparison of Rendering to Composting

Figures 1 and 2 provide a direct comparison of fossil fuel consumed and greenhouse gases emitted when animal byproducts are rendered versus being co-composted with other organic materials. The inlet basis of the two input/output diagrams is the same (1000 kg of animal byproducts are processed), but the outlet gates are not comparable. Rendering produces fat and protein that is used in animal feeds and other applications; composting produces a soil amendment product. Compost is claimed to have many soil amendment properties (21), but the only characteristics proven to be attributable to co-composted meat byproducts are an increase in total nitrogen of the following compost and an increase in ammonium nitrogen specifically.

Fat and protein produced by rendering 1000 kg of meat byproducts are worth about 20 times the economic value of the additional nitrogen content that would be obtained by co-composting the same meat byproducts. Furthermore, co-composting meat byproducts rather than rendering them results in the emission of at least 10 times as much greenhouse gas, measured as CO_2 equivalents. [The two Canadian studies cited earlier (19, 20) provide the only known comparative data between composting with and without meat byproducts present, and they actually indicate 12 to 17 times higher CO_2e emissions.] The only measure considered in this report that favors composting over rendering is the consumption of fossil fuels. Transportation of meat byproducts is the only significant consumer of fossil fuel if analysis stops at the outlet gate of the composting operation and manure would have been composted anyway. In contrast, rendering involves considerable fossil energy consumption to produce heat required for the process as well as fuel for transportation of the meat byproducts from their source to the rendering plant.

Figures 1 and 2 provide what most people would consider to be a valid, direct comparison of rendering and composting since the economic value of the rendered products is so much larger than the economic benefit of co-composting the meat materials. But to a strict proponent of life cycle assessment as a decision tool, the comparison is not valid unless the starting and ending points are equivalent. One way to establish the required equivalence is to use a consequential life cycle assessment. For this purpose, the following argument is proposed.

Premise: Current markets demand two distinctly different products:

- metabolizable energy in the form of fat or oil and protein meal
- nitrogen fertilizer.

Scenario A: Meat byproducts are rendered to produce metabolizable energy that is used in animal feeds. As a consequence more nitrogen fertilizer must be produced from natural gas.

Scenario B: Meat byproducts are co-composted with other organic matter to produce higher nitrogen compost for soil amendment. As a consequence more soy oil and meal must be produced to provide metabolizable energy for use in animal feeds.

The comparison of Scenarios A and B is summarized in Table 1. Scenario A was created by adding the data in Figure 1 to the corresponding data provided in the above section titled Production of Nitrogen Fertilizer. Scenario B was created by combining the data in Figures 2 and 3, but adjustments were necessary. The compost TN and GHG emission data differed in the cow and calf studies so the results of the two studies shown in Figure 2 were averaged. Also data in Figure 3 were multiplied by 1.5 so that the soy products would provide the same metabolizable energy as the rendered products in Figure 1.

Table 1. Comparison of two scenarios in a consequential life cycle assessment of rendering meat byproducts versus co-composting them with other organic matter.
Scenario A: Meat byproducts are rendered to produce metabolizable energy for animal feed. As a consequence more nitrogen fertilizer must be produced from natural gas.
Scenario B: Meat byproducts are co-composted with other organic matter to produce higher nitrogen compost for soil amendment. As a consequence more soy oil and meal must be produced to provide metabolizable energy for animal feeds.

	Scenario A rendering plus fertilizer production	Scenario B composting plus soy production
Inputs		
Meat byproducts, kg	1,000	1,000
Fossil fuel, MJ	3,100	2,500
Outputs		
GHG emissions, kg CO_2e	250	3,600
Sequestered carbon, kg CO_2	750	1,100
Net GHG emission, kg CO_2e	-500	2,500
Fat or oil, kg	200	140
Protein meal, kg	220	560
Metabolizable energy, MJ	10,000	10,000
Fertilizer, kg total nitrogen	15	15
Value of all products, $	280	420

When rendering is compared to composting in the consequential analysis represented in Table 1 as opposed to a simple direct comparison, the relative differences in the numbers changes, but the overall conclusions do not. Rendering still requires the consumption of more fossil fuel, but the difference between the two processes is much smaller in the consequential analysis. Composting still emits more than ten times as much greenhouse gas as rendering. The net GHG emission is negative for rendering because of the sequestration credit applied to the products, but the credit awarded to soy products is dwarfed by the direct emissions from composting. Several caveats about this analysis should be considered:

- Each number in Table 1 was rounded to two significant figures to reflect uncertainty in the results. The actual precision of the numbers in the table is not known because the data used to compile this report were derived from many sources that did not provide rigorous statistical analyses of data quality.
- Meat byproducts are assumed to be a starting material in each scenario. If meat production were added to each scenario to take the inlet gate back to the cradle, data would be added for the production of fertilizer and pesticides to grow grain to feed to animals that would ultimately be slaughtered to product meat and meat byproducts. The fossil energy consumption and greenhouse gas emissions of Scenario A and Scenario B would increase by the same amount so the comparison between the two scenarios would not change.
- The data in Figure 2 and thus the data on Scenario B in Table 1 do not include fossil fuel consumption and GHG emission that would result from composting manure. They include only the fossil energy consumption and GHG emissions that are attributable to the co-composted meat byproducts. It is assumed that the manure and other organic materials co-composted with meat byproducts in Scenario B would be composted anyway if Scenario A were used.
- The economic value of Scenario B is 50% higher than that of Scenario A in this analysis because the quantity of soy products was increased by 50% to provide the same amount of metabolizable energy. If the comparison were scaled to equate the combined economic value of the products in each scenario, Scenario B would produce less metabolizable energy than Scenario A, and Scenario B would have a larger advantage in fossil fuel efficiency and a smaller disadvantage in greenhouse gas emissions.
- One potential weakness of this argument is that soy oil is not currently a common component in animal feeds because it is more expensive than available alternatives, such as rendered fat and bakery waste. Nevertheless, soy products were chosen for comparison because they are similar in composition to rendered products and could be used as a direct substitute, and a complete life cycle assessment for soy products has been developed by the United Soybean Board. Some information is available on fossil fuel use and greenhouse gas emissions associated with bread production, but no LCA could be found for bakery waste.

Conclusions

This report compares environmental effects of rendering and composting as alternative methods of handling meat byproducts. It also compares the environmental effects of producing rendered fat and protein meal as opposed to soy oil and protein meal. Only two environmental impacts are considered in each case: fossil fuel consumption and greenhouse gas emissions. Numerous other impacts could be considered and compared (e.g., water use, land use, a specific defined risk to human health, etc.), but data are more readily available on fossil fuel consumption and GHG emission than on other impacts, and these two impacts are among those mentioned most frequently by business entities and the news media. The following conclusions were drawn from the analyses presented.

1. If a direct comparison is made between rendering and composting a particular quantity of meat byproducts, rendering will require the consumption of about 10 times as much fossil energy, but composting will emit at least 10 times more greenhouse gas.

2. To compare the products of rendering to soy oil and meal, a basis of comparison must be chosen because the chemical composition and relative amounts of fat and protein produced by the two methods are not the same. If the comparison is made on the basis of equal economic value of the products, the production of soy oil and meal consumes about 60% as much fossil energy as the production of rendered fat and protein meal, and the two processes emit virtually equal quantities of greenhouse gas.

3. The soybean industry makes the valid claim that soy products contain sequestered carbon dioxide as a result of the uptake of CO_2 from the atmosphere by soybean plants. This credit might be short-lived depending on the use of the soy products, but the analysis used in this work stops at the product loading dock of the soy processing plant. Credit for sequestered CO_2 gives soy products an advantage over rendered products with respect to GHG emissions unless a similar claim can be made for fat and protein meal. To make this claim the rendering process must be traced back to the growth of grain for animal feed, and all GHG emissions resulting from feed growth and preparation and from animal growth and processing must be allocated to the meat produced for human consumption or to other meat byproducts that are not rendered. If rendered products are not held responsible for any of the GHG emissions associated with meat production, <u>and</u> the carbon in rendered products is credited as sequestered CO_2 since it originated as atmospheric CO_2 taken up by grain plants, then the net GHG emission associated with rendered products is negative. It is also essentially equal to the net GHG emission associated with soy products that have the same economic value.

4. If rendered and soy products are compared on the basis of equal metabolizable energy rather than equal economic value, approximately 50% more soy oil and meal must be produced. Thus using metabolizable energy as the basis of comparison increases the fossil fuel consumed to make soy products to about 85% of that consumed to make an equal amount of rendered products. Using metabolizable energy as the basis of comparison means that production of soy oil and meal actually emits 50% more

greenhouse gases than producing an equal amount of rendered products. But using this basis also increases the sequestration credit of soy products by 50%. Therefore, if metabolizable energy is used as the basis of comparison and a sequestration credit is allowed for both rendered and soy products, soy products are preferable over rendered products with respect to GHG emissions

5. Life cycle assessments that compare alterative services or products are considered to be more valid if the boundaries are expanded to minimize differences between the products and services offered. The consequential analysis between Scenario A and Scenario B in this report attempts to accomplish that goal. The inputs to each scenario are 1000 kg of meat byproducts and various products of nature that are accounted for with respect to fossil fuel consumption and greenhouse gas emission. The outputs of each scenario are 15 kg of nitrogen fertilizer and a fat or oil and a protein meal that together provide 10,000 MJ of metabolizable energy. Scenario A, which renders the meat byproducts and produces nitrogen fertilizer from natural gas, requires the consumption of more fossil fuel. Scenario B, which composts the meat byproducts and produces soy oil and meal, emits more than ten times as much greenhouse gas as Scenario A. The net GHG emission is negative for Scenario A because of the sequestration credit to the products, but the credit awarded to soy products in Scenario B is dwarfed by the direct GHG emissions from composting.

6. The data in this report on rendering and soy production are averages obtained from numerous individual processing plants. Data on composting came from two specific studies that compared GHG emissions from conventional manure and straw composting to those in which meat byproducts were co-composted with manure and straw. The conclusions drawn from this study are not necessarily valid for comparing a specific plant or operation of each type. The comparisons presented are more likely to be indicative of industry averages or common practice.

7. Given the numerous sources of data used in this report and the lack of statistical data analysis in most of the references, it is not possible to make definitive statements about accuracy or precision. We certainly think differences of more than 50% between compared values are significant, but smaller differences might not be. Also the reader should consider carefully the validity of assumptions made in each section of the report.

Appendix A: Rendering of Animal Byproducts
Charles H. Gooding

This appendix is an abbreviated version of reference 1: Gooding, C. 2012. Data for the carbon footprinting of rendering operations, *J. Industrial Ecology*, **16**(2): 223-230.

An overview of rendering operations
Rendering plants process a variety of raw materials including whole animals that die from disease and other miscellaneous causes, bone, feathers, blood, and offal (viscera and trimmings) from slaughterhouses, and grease from restaurants. On average these raw materials are nearly 60% water. The other 40% of the incoming mass is converted into two broad product categories, fats and protein meals.

Anderson (29) provides a concise description of modern rendering operations. Most industrial-scale rendering plants use the dry continuous process, which is illustrated in Figure A1. Unless raw material is generated on site in a slaughterhouse, it is normally received by truck or rail. The material is ground to a uniform size and sent to a continuous cooker where it is heated to 115 to 145ºC to kill pathogens, evaporate moisture, and melt fat. The resulting slurry is discharged to a drainer conveyor where liquid fat is separated from solid protein and bone. Fat leaving the settling tank beneath the conveyor is centrifuged to remove fine solids and then sent to finished storage and packaging.

Figure A1. Depiction of a continuous rendering system [Figure 1 from Gooding (1)].

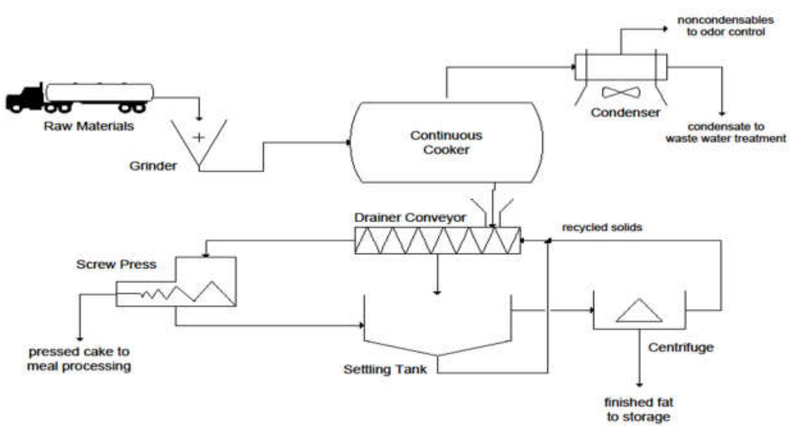


Figure 1. Continuous rendering system.

Solids are recycled from the centrifuge back to the drainer conveyor, joining new feed from the cooker and solids recycled from the settling tank. Most solids retained by the drainer conveyor are discharged to screw presses, where the residual fat content is reduced to 10 to 12 weight percent. Larger solid particles may be sent back to the cooker. Fat pressed from the solids is recycled to the settling tank. The protein-rich cake leaving the screw presses goes to final meal processing, packaging and storage.

Water vapor leaving the cooker passes through an entrainment trap to prevent liquid and solid particles from exiting with the vapor. The vapor is condensed and sent to wastewater treatment along with other wastewater streams generated in the plant. Non-condensables are pulled from the condenser by a blower and processed through an odor control system.

Cookers require a considerable amount of steam, which is usually generated by burning purchased fuels such as oil and natural gas as well as some of the fat produced by rendering. Combustion associated with steam generation is the primary source of carbon dioxide emissions from rendering operations. Most rendering plants conserve fuel and reduce energy costs by employing waste heat recovery to generate hot water used in the process.

Pertinent characteristics of raw materials and products

Table A1 shows relative amounts and important characteristics of 13 common raw materials that might enter a rendering plant. Typically offal, bone, feathers, and blood come from slaughtering operations. Whole dead animals come from farms or feedlots, and raw grease is collected from restaurants. Data on the typical composition and quantity of materials rendered in North America are available from several sources (17, 30 - 34). The numbers shown in Table A1 were determined by cross-referencing these sources to estimate the total amount of each raw material processed in North America annually and then dividing by 300, the approximate number of plants in operation. The results were rounded to define a hypothetical average plant that processes 100,000 tonne/year of raw material. The percent of fat, protein, and water shown for each raw material is typical, but specific contents vary with location, time of year, and source of the feed stock.

Table A2 shows estimates of the annual production rates of animal fat (BFT) and five types of protein meal that would be produced in a rendering plant that processed the raw materials shown in Table A1. The estimates in Tables A1 and A2 are consistent with respect to mass balances on fat and protein, assuming 1% loss of organics to wastewater treatment. An estimate is provided for the weight percent carbon in each product category (33). Overall 42% of the raw material mass entering the plant leaves as product, 1% of the organic matter is lost to wastewater treatment, and 57% of the raw material is water that is boiled off or drained from the process.

Table A1 Typical characteristics of raw materials entering a rendering plant.

Type	tonne/yr	% fat	% protein	% water
Steer offal and bone	34200	31	21	48
Cow offal and bone	5000	15	30	55
Calf offal and bone	1600	10	23	67
Hog offal and bone	19000	28	14	58
Sheep offal and bone	300	28	22	50

Poultry offal	20000	10	25	65
Poultry feathers	8200	0	33	67
Whole cattle	5200	12	26	62
Whole hogs	2000	30	28	42
Whole sheep	100	20	25	55
Whole poultry	1000	15	25	60
Raw grease	300	65	10	25
Blood	3100	0	17	83
TOTAL	100000	20.5	22.2	57.3

Table A2 Products that would result from rendering the material in Table A1.

Type	**tonne/yr**	**% carbon**
BFT (animal fat)	20300	75.9
Meat and bone meal	10400	24.3
Poultry byproduct meal	5200	28.7
Feather meal	2700	37.5
Pork meal	3200	25.6
Blood products	500	37.5
TOTAL	42300	50.7

Transportation of raw materials

Rendering plants that are integrated with a slaughterhouse receive raw materials generated on site via conveyor belt, fork lift, or by other short range vehicular transportation. Independent rendering plants normally receive raw materials by truck. The amount of fossil fuels burned in these trucks and the emission rate of greenhouse gases, primarily carbon dioxide, depends on the quantity of raw materials received at the plant, the typical size of the load, the two-way distance traveled, and the fuel efficiency of the vehicle. The numbers shown in Table A3 are typical for an independent rendering plant that receives raw materials and dispenses products by truck. The average size load, distance traveled, and fuel efficiency were extracted from a survey of operations at 25 independent rendering plants reported by Lopez et al. (27). The survey indicated that, on average, products are trucked about twice as far as raw materials, but the mass of products leaving the plant is less than half the mass of raw materials entering, so the fuel use and CO_2 emissions due to product transportation are roughly comparable to those resulting from raw material transportation. The estimates for product transportation shown in Table A3 were not included in the life cycle assessment developed in this report because it is based on the outlet gate being at the product loading dock of the rendering plant.

Table A3 Off-site transportation for the rendering plant illustrated.

	tonne/yr	**tonne/load**	**avg km/load**	**fuel use L/km**
Raw materials	100000	20	300	0.40
Products	42300	25	600	0.40

Burning of process fuels and purchase of electric power

Table A4 illustrates typical fuel use and purchased power consumption for a plant rendering 100,000 tonne/yr of raw material. The values shown were calculated from additional survey data published by Lopez et al (27). The Lopez paper reports data in terms of energy use per tonne of rendered product and provides additional details on the survey participants and variability of response data. Average quantities of grease and fat burned on site are shown along with other fuels. In some rendering plants methane is produced by anaerobic waste water treatment and burned on site, but that is accounted for separately in Table A5 below.

Table A4 also shows energy content (lower heating value) for each fossil fuel and carbon dioxide emission equivalents for each fuel burned in a rendering plant. With the exception of animal fat and grease, emission factors were calculated from life cycle inventories published by the National Renewable Energy Laboratory (28). Carbon dioxide emission factors for grease and fat were estimated from average composition data (27) and stoichiometric calculations, assuming complete combustion.

Table A4 Fuel burned and power purchased for the rendering plant illustrated.

Type of fuel	Units	annual use	MJ/unit	kg CO2e/unit
Natural gas	SCM	3,100,000	35	2.0
No. 2 oil	L	15,000	38	2.7
No. 6 oil	L	1,700,000	40	3.1
Grease	kg	220,000		2.7
Animal fat	kg	1,200,000		2.8

Purchased electricity 6,800,000 kWh

grid breakdown	% generation	kg CO2e/kwh
coal	52	1.0
natural gas	16	0.6
oil	3	1.0
renewables	1	0.0
nuclear	20	0.0
hydro	7	0.0
other	1	0.0

The breakdown of power generation by type of fuel in Table A4 corresponds to the U. S. grid average as reported by the NREL (28). GHG emissions for each fuel were taken from the same source. Life cycle data reported by NREL for electricity production at hydroelectric or nuclear power plants indicate that CO_2e emissions from these sources are negligible to three significant figures compared to emissions from other sources of purchased electricity and to fuel burning contributions at a rendering plant. Renewable fuels and "other" means of generating electricity also contribute negligible net carbon dioxide to the environment. Production of nitrous oxide and methane and their CO_2 equivalent factors were included in the calculations. Despite the high GWP factors of methane and nitrous oxide, the NREL emission data indicate that GHG contributions from these gases are negligible to two significant figures for all fuels listed.

Wastewater treatment

The flow rate and concentration of wastewater from a rendering process can vary considerably with time and from one rendering plant to another. Carbon in the organic compounds that is sent to wastewater treatment has three potential fates:

- Aerobic conversion into carbon dioxide
- Anaerobic conversion into methane
- Aerobic or anaerobic conversion into solid biomass

Aerobic wastewater treatment is used more often in rendering plants than anaerobic treatment. The most common measure of organic concentration in wastewater is biological oxygen demand (BOD), which is the amount of oxygen consumed by aerobic, microbiological reactions that occur when the waste is degraded, primarily into carbon dioxide and water. A related quantity, carbonaceous BOD, or CBOD, excludes oxidation of organic nitrogen, so CBOD is the most direct indicator of potential CO_2 emissions. A third alternative, chemical oxygen demand or (COD), can be determined quickly, but like BOD it usually includes contributions from nitrification and other oxygen-consuming reactions that do not produce CO_2. The COD/CBOD ratio depends on the specific composition of the waste, but 1.5 is a typical value (35). Sindt (36) reports that CBOD concentrations of individual waste streams produced in a rendering plant range from about 4000 to 10,000 mg/L. Usually the CBOD concentration must be reduced to 10 to 25 mg/L by wastewater treatment before discharge. Each kg of CBOD entering aerobic waste treatment ultimately results in about 1.5 kg of CO_2 being released into the atmosphere (36).

Studies of municipal wastewater treatment systems by Czepiel et al. (37, 38) showed that emissions of methane and nitrous oxide from properly operated activated sludge systems are small. Mass emission ratios calculated from measured data were on the order of 10^{-3} for CH_4:CO_2 and 10^{-4} for N_2O:CO_2. In a more recent study, Ahn et al. (39) showed that N_2O emissions can be up to an order of magnitude higher from treatment systems designed to maximize biological nitrogen removal from wastewater. With 100-year GWP factors applied, the results of Czepiel indicate that CO_2 equivalent emissions from aerobic treatment are about 5% higher than CO_2 emissions alone. In the worst case, emissions consistent with Ahn's estimate could increase the CO_2e estimate to 30% higher than CO_2 alone.

Anaerobic wastewater treatment plants use different microorganisms in an oxygen-deficient environment to convert organic compounds into a mixture of CO_2, CH_4, and other species. Properly operated anaerobic systems capture and usually burn the gases produced so that nearly all of the carbon in the wastewater is ultimately released to the atmosphere as CO_2. Thus anaerobic and aerobic treatment facilities have the same effect on CO_2 emissions unless significant quantities of methane are released to the atmosphere rather than being burned. If methane is released during wastewater treatment, the potential impact is much larger due to the higher GWP of CH_4 emissions.

In summary, Sindt (36) reports that the typical wastewater treatment requirement in a rendering plant is 0.005 tonne of CBOD per tonne of raw material rendered. For a plant that renders 100,000 tonne/yr of animal byproducts, this translates into 500 tonne/yr of CBOD being sent to a wastewater treatment process, and 1.5 tonne of CO_2 is released per tonne of CBOD. If aerobic wastewater treatment is used, Czepiel (37, 38) indicates that about 0.2% of the carbon will be released as methane, which will result in CO_2 emission equivalents that are 5% higher than simply converting all carbon to carbon dioxide. For anaerobic treatment systems that capture and burn methane, methane losses to the atmosphere would be about 5%, based on IPCC guidelines for estimating greenhouse gas emissions (40). Anaerobic digestion typically converts 75% of the organic carbon that enters the system into biogas with a molar composition of 25 to 50% CO_2 and 50 to 75% CH_4 (41). This implies that as much as 50% of the carbon mass entering an anaerobic treatment facility could be released as methane if the biogas is not captured.

Summary of fossil energy use and greenhouse gas emissions in rendering operations
Table A5 summarizes annual fossil fuel use and carbon dioxide emission equivalents for the typical rendering plant illustrated in Tables A1 through A4. Emissions due to transportation of raw materials were determined by calculating total fuel consumption and applying a diesel fuel

emission factor of 3.0 kg CO_2e/L fuel consumed (28). Emissions from fuel combustion in the rendering plant were determined by multiplying annual consumption of each fuel by the corresponding emission factor shown in Table A4. As noted before, burning of grease and fat recovered from rendered materials is included in Tables A4 and A6 because it results in CO_2 emissions just like burning any other fuel.

Table A5. Summary of fossil fuel use and greenhouse gas emissions from a plant that renders 100,000 tonne/yr of animal byproducts and produces 42,000 tonne/yr of fat and protein meal.

	MJ/yr	**tonne CO2e/yr**
Transportation of raw materials	23,000,000	1,800
Burning purchased fuels	177,000,000	11,500
Burning grease and fat	not fossil fuel	4,000
Purchased electricity	58,000,000	4,400
Wastewater treatment	electricity only	800

The fossil energy use attributed to electricity purchased for the rendering plant was calculated by summing the kWh attributed to fossil energy sources and multiplying by 12 MJ/kWh, which assumes that 30% of the lower heating value of the fuel burned by the electric utility company is delivered to the rendering plant as electricity. This conversion factor is appropriate for electricity generated in a steam cycle. It also assumes transmission losses of 9%. To determine CO_2 emission equivalents attributable to purchased electricity, the total kWh of electricity purchased was first apportioned to the different methods of power generation using the percentages provided. Each result was then multiplied by the emission factor that applies to the method of generation, and the emission equivalents were summed to provide the final result.

The estimates in Table A5 indicate that raw material transportation and rendering plant operations emit about 0.18 kg CO_2 equivalents/kg of rendered raw material or 0.43 kg CO_2e/kg of product. Inclusion of the emissions attributed to the electricity purchased for use in the plant adds 22% to each of these ratios. In total, direct and indirect GHG emissions are equivalent to converting about 23% of the carbon that enters the plant into carbon dioxide and releasing it to atmosphere. In the typical rendering plant illustrated, fuel burning on site accounts for 62% of the total fossil energy consumption and 69% of the GHG emissions. Electricity purchased for use in the plant accounts for 20% of both fossil energy consumption and GHG emissions. Raw material transportation accounts for 8% of fossil energy use and GHG emissions. About 1% of the carbon that enters the rendering plant leaves as CO_2 emissions from wastewater treatment if aerobic digestion is used. It should be noted, however, that anaerobic wastewater treatment has the potential to increase CO_2 equivalent emissions substantially if a substantial fraction of the methane generated is allowed to escape.

Appendix B: Composting of Animal Byproducts
David Carey and Charles Gooding

Published studies have examined a variety of factors that come into play with the composting of animal byproducts. Variables include methods of operation such as open versus enclosed composting, pre-processing (e.g. grinding), active versus passive aeration, type and amount of bulking material used, compost pile or windrow turning, and biogas capture. Environmental conditions play a role in determining decomposition rate, liquid and gaseous emissions, pathogen reduction, nitrogen mineralization and demineralization, oxygen availability, volume and mass reduction, energy and space requirements, and cost. These variables can also influence properties of the final compost such as C and N content, moisture content, pH, porosity, nutrient content (N, P, and K), particle size, stability, bulk density, microbial activity, odor, and homogeneity. In addition, bio-security is an important factor that must be considered when evaluating animal byproduct disposal processes and the use of resulting products.

Greenhouse gas emission data resulting from co-composting of animal byproducts

Numerous experiments and demonstrations have been conducted to investigate the feasibility of co-composting animal byproducts with materials such as manure, straw, and sawdust. Only two known studies have provided a direct comparison of the greenhouse gas (GHG) emissions that result from composting with and without animal byproducts present. Xu et al. (19, 20) conducted two large-scale studies on the co-composting of cattle mortalities with manure and straw in western Canada. In each project two compost windrows were constructed, each roughly 2 m wide, 2 m high, and 30 m long. The control windrow contained only manure and straw, and the other was identical except for the inclusion of cattle mortalities. In the first study whole, partially frozen, mature cattle that had died of natural causes made up 10.2% of the initial wet weight of the windrow. In the second study whole, partially frozen calves that had died of natural causes made up 5.4% of the initial wet weight. In each study emissions of carbon dioxide, methane, and nitrous oxide were monitored for approximately 300 days. Each windrow was turned twice, at roughly 1/3 and 2/3 of the total duration of the study. Temperature and oxygen levels in the compost windrows were also monitored, and the spatially averaged composition of the final compost was determined. The published papers (19, 20) contain much more detail about the conditions and procedures used and the results measured and observed.

Table B1 shows the total emissions of GHGs from each windrow over the entire duration of each study. Table B2 shows a comparison of various measurements made on samples taken from twelve locations in each of the final compost windrows. Control windrows that consisted of manure and straw only are designated CK, and the windrows containing animal mortalities are designated CM. For each study CK vs. CM values in the same column followed by different letters (a and b) are significantly different at a 90% confidence level ($p < 0.05$), while values followed by the same letter (a) are not. Compared to the control, all three greenhouse gases were emitted in significantly higher quantities from the windrow containing cattle mortalities. Most of the carbon dioxide and methane was emitted in the first few weeks of each study. Maximum nitrous oxide emissions occurred somewhat later. Emissions of all three GHGs were relatively low after the first turning of the windrows.

Table B1. Comparison of total emissions from windrows with and without animal byproducts.

Study	Treatment	C as CO_2	C as CH_4	N as N_2O
		g / kg dry manure		
Xu et al. (16) (cattle mortalities)	CK	35 a	1.1 a	0.46 a
	CM	78 b	3.2 b	0.82 b
Xu et al. (17) (calf mortalities)	CK	58 a	0.14 a	0.10 a
	CM	65 a	3.2 b	0.40 b

Table B2. Comparison of final compost composition with and without animal byproducts.

Study	Treatment	TC	TN	N as NH_4^+	N as NO_3^-	N as NO_2^-	C/N
		g / kg	g / kg	mg / kg	mg / kg	mg / kg	
Xu et al.(16) cattle mortalities	CK	168 ^{a}	9.5 ^{b}	27 ^{b}	85 ^{a}	24 ^{a}	17.7 ^{a}
	CM	181 ^{a}	11.9 ^{a}	725 ^{a}	169 ^{a}	0 ^{a}	15.3 ^{b}
Xu et al. (17) calf mortalities)	CK	182 ^{a}	10.3 ^{a}	30 ^{b}	121 ^{b}	0 ^{a}	17.8 ^{a}
	CM	185 ^{a}	12.2 ^{a}	195 ^{a}	740 ^{a}	6 ^{a}	15.3 ^{b}

Overall the emission results from the mature cattle composting study indicated that 77% of the carbon present in the original wet carcasses was emitted as CO_2 and 4% as CH_4. These results agreed remarkably well with a carbon balance based on the initial windrow and final compost compositions, which indicated that 81% of the carbon in the cattle mortalities was lost. The study with composted calves had somewhat different and less consistent results. Emission data indicated that 45% of the carbon originally in the calves was emitted as CO_2 and 19% as CH_4 while a mass balance comparing initial windrow and final compost composition indicated that 82% of the total carbon in the original calf carcasses was lost.

Based on direct emission measurements and estimates of nitrogen initially present in the animal byproduct protein, data in Table B1 indicate that 6% of the nitrogen in the whole cattle mortalities and 9% of the nitrogen in the calf mortalities was emitted as N_2O. In contrast, comparing Table B2 measurements on the final compost to estimates of the original nitrogen in protein indicate that 59% of the nitrogen in the whole cattle carcasses and 39% of the nitrogen in the calf carcasses was lost. Some if not all of the additional nitrogen loss could have been in the form of NH_3 emissions, which were not measured.

In the whole cattle study 29% of the TN in the final compost was present as ammonium nitrogen (NH_4^+) and 4% as nitrate (NO_3^-). In the calf study only 8% of TN was present as NH_4^+, but 32% was present as NO_3^-. The higher NO_3^- content seen in the calf study might be due to the existence of higher oxygen concentrations in the windrow. In the whole cattle study regions of low oxygen concentration (0-3%) were noted. Oxygen concentrations were not reported in the calf study, but concentrations of >5% are recommended to maintain aerobic activity (42-44). Nitrate is a more readily plant available form of N and is an important component in some commercial fertilizers. NH_4^+ to NO_3^- ratio is also known to affect plant growth (45). To meet crop production needs, additional fertilizer containing nitrogen and phosphorus is usually applied when compost is used as a soil amendment or organic fertilizer (46). Therefore, increased TN, NH_4^+, and NO_3^- contents in compost increase its agronomic value and displace the need to produce some of the additional inorganic nutrients.

Other studies that provide relevant information on animal byproduct composting

Hao (47), one of the researchers involved in the Xu et al. studies, published with coworkers an earlier study that examined C and N balances and GHG emissions from the composting of cattle feedlot manure with cereal straw or wood chips. The compost materials were different and a comparison to mortality composting was not done, but compost windrows were constructed in a similar way and fuel use to manage the windrows was evaluated. Hao et al. reported 0.266 L diesel fuel per turn per 1000 kg of compost for straw bedding and 0.220 L for wood chip bedding. With an emission factor of 3.2 kg CO_2e/L for provision and combustion of diesel fuel and successful composting in the previous study with only two turns, the GHG emissions associated with fuel use are quite small (<0.1%) compared to direct emissions from the compost.

Some researchers have expressed concerns about mortality composting in climates where temperatures are below 0°C (48) and have also recommended against stacking more than a single layer of mortalities in a windrow (49). Stanford et al. (50) demonstrated successful open-air windrow composting of single, double, and triple layered cattle mortalities over a period of 9 months using barley straw and stockpiled manure despite ambient temperatures below 0°C and the use of initially frozen cattle mortalities. The composting resulted in a product containing no apparent soft tissue and some small bone fragments. Coliform bacteria levels were acceptably low under EPA regulations for final composts (51), and no odor or apparent leaching was observed. Stanford et al. concluded that although open-air mortality windrows may be prone to over-wetting, they were suitable for use in semi-arid Alberta and that stacking up to three layers of cattle mortality is an effective space-saving option for mortality composting in this climate.

Animal bones contain phosphorus and potassium so the inclusion of mortalities in compost contributes to the plant-available nutrient content (N, P, and K) of the compost, and also yields compost with an N:P ratio closer to the uptake ratios for wheat, corn, and grain sorghum (52). Compost is often applied on a nitrogen basis and, because the N:P ratio of compost is often lower than the crop uptake ratio, phosphorus is applied in excess. Over-application of phosphorus can result in soil phosphorus accumulation and lead to nutrient runoff and eutrophication problems. This suggests that inclusion of mortalities in compost could provide a better suited balance of compost nutrients and help mitigate problems associated with over application of phosphorus while still meeting crop nitrogen requirements.

Mukhtar et al. (53) examined composting as a low maintenance carcass disposal method using in-bin, static piles to compost whole cow and horse carcasses with spent horse bedding as a co-composting material. Four piles were constructed, two with wooden pallets placed below the carcass to provide continued aeration without additional maintenance. The horse on pallet, horse without pallets, cow on pallets, and cow without pallets piles used various weight ratios of co-composting material to animals. Piles without pallets were turned at 3 and 6 months after construction, and piles with pallets were turned once, 6 months after construction. The only additional moisture provided after pile construction was from rainfall. After six months all but the horse on pallet pile were combined into one large pile. After nine months the horse on pallet pile and the large combined pile were sampled and analyzed for C:N, pH, moisture content, C, N, P, K, salmonella, and fecal coliform content.

In Figure B3 below, which is Table 2 from the original source, the results are compared with those from co-composting material alone. The finished horse on pallet pile compost showed a higher N, P, and K content and lower C:N ratio and had pathogenic concentrations within the limits of standards for high quality compost products. The finished large pile compost also showed a lower C:N ratio and higher N content and had acceptably low pathogen levels, but had lower P and K content. After nine months a high degree of biodegradation was observed with only faint odors and the final product was ready to be land-applied without further processing. Chemical analysis showed increased plant fertilizer nutrients (N, P, and K) in one of the horse mortality piles when compared to co-composting material alone, representing value added for use as fertilizer. The other three mortality piles combined showed only a small increase in N (and a decrease in P and K), indicating that the inclusion of cow and horse mortalities and the treatment of this compost did not result in an end product with much (if any) additional fertilizer nutrient value.

Table B3. Horse co-composting data from Mukhtar (53).

Table 2. Chemical and physical properties of co-composting material and carcass compost piles.

Parameter (as is basis)	Co-composting material	Small compost pile *	Large compost pile**
C (mg/kg)	167,781 (±16,844)[1]	123,258 (±35,161)	96,292 (±10,886)
N (mg/kg)	3,431 (±414)	6,669 (±2,479)	4,000 (±611)
C:N	49.1 (±4.8)	19.3 (±4.4)	24.4 (±3.5)
P(mg/kg)	1,313 (±119)	1,659 (±623)	1,247 (±450)
K(mg/kg)	3,806 (±697)	4,512 (±677)	3,220 (±859)
pH	7.7 (±0.13)	7.8 (±0.07)	7.7 (±0.44)
MC (%)	41.4 (±2.6)	42.7 (±11.5)	51.5 (±5.4)
Salmonella[2]	NA	not detected	≤2
Fecal coliform[3]	NA	55 (±26.2)	227 (±388)

* Refers to horse on pallets compost pile
**Refers to combined compost pile of horse and cow without pallet and cow with pallet.
[1]Mean values with standard deviations in parentheses. n=5.
[2]Maximum probable number (MPN) per 10 gram of material on as is basis.
[3]Colony Forming Units (CFU) per 10 gram of material on as is basis.

Rozeboom et al. (54) conducted a demonstration project in conjunction with Jones Farm Meats, LLC, Saranac, Michigan in which meat processing by-products (including meat scraps, fat trim, bones, internal organs, gastro-intestinal tract contents, and wash-water solids from beef, pork, goat, cervidae, bison, and lamb) were composted using clean, dry hardwood sawdust as a carbon source (co-composting material/bulking agent). An in-bin, static pile system was constructed to compost about 11,600 lb of by-products produced each week. It was designed to retain leachate that may result from rainfall up to 4.25 inches. By-products were ground before composting, which resulted in increased energy use and maintenance, but allowed quicker and easier processing of the by-products by reducing bone size, increasing homogeneity, and reducing the volume by 250%. Kalbasi et al. (55) noted that pre-grinding can also reduce the amount of co-composting material necessary to compost a given amount of animal by-product. Chemical analysis of the meat by-product was 79.2% dry matter, 71.4% fat, 5.0% crude protein, and 1.5% ash. Composting reduced the total volume of the compost mixture by 42%. Chemical analysis of the final compost is shown below in Figure B4.

Figure B4. Characteristics of compost produced from meat byproducts and sawdust.

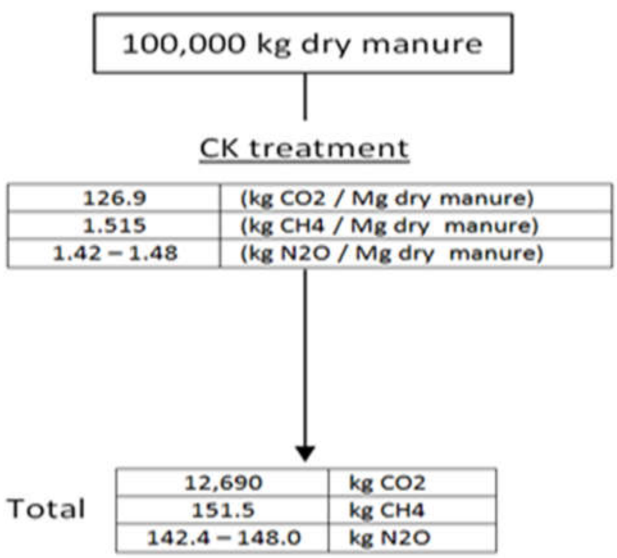
Description of finished compost (wet basis)						
Density, lbs./yd3	Moisture, %	Total N, %	NH_4, %	P_2O_5, %	K_2O, %	Ca, %
1,010	49	1.22	0.50	0.90	0.29	1.12

The final compost product was estimated to contain $11.60/ton worth of commercial inorganic fertilizer nutrients. The study concluded that this composting setup could allow Jones Farm to decrease costs compared to rendering services, assuming a useful life of the composting facility of 30 years or more.

Co-composting in an feedlot environment

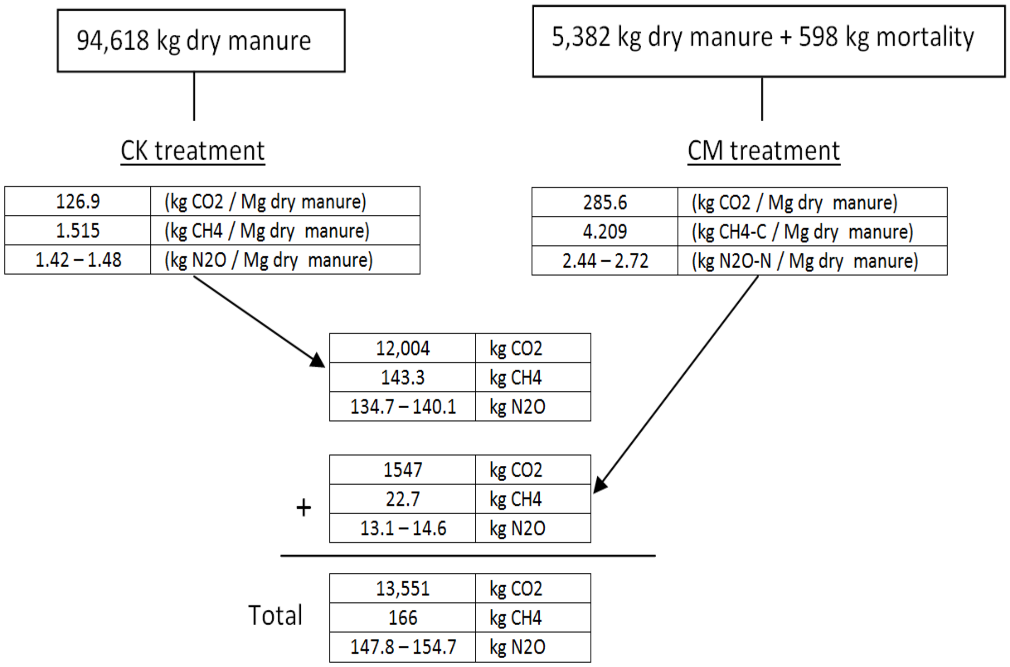
Direct comparison of compost windrows created by Xu et al. in the adult cattle study (19) showed that the mortality-containing windrow had a considerably higher environmental impact in the form of GHG emissions. But the emissions attributable to the meat were relatively small compared to those attributable to the manure. In a typical feedlot operation Lonergan et al. (56) report that mature cattle average 500 kg in mass, and approximately 1000 kg of dry manure is produced per cow per year. Based on the data of Xu et al. (19), Figure B5 shows the greenhouse gas emissions that would result from composting 100,000 kg of dry manure produced by 100 head of cattle in a feedlot for one year.

Figure B5: Greenhouse gas emissions from composting manure without mortalities.



Lonergan and coworkers (56) also estimated the mortality rate in a feedlot operation to be 1.3%. With the 1:9 weight ratio of mortality to manure used by Xu, only 5% of the total manure produced in a feedlot would be needed for mortality composting, leaving the remaining manure to be processed in the same manner as it would be otherwise. It is reasonable to assume that this manure would be composted to produce a stabilized soil amendment product. Figure B5 illustrates the co-composting of feedlot mortalities with manure and the separate composting of the residual manure.

Figure B5. Greenhouse gas emissions from co-composting cattle mortalities with manure in a feedlot and composting the residual manure.



Comparison of Figures B5 and B6 indicates that the inclusion of cattle mortalities would result in an increase in emissions of 861 kg CO_2, 14.5 kg CH_4, and 5.4 to 6.7 kg N_2O, depending on how the windrow was turned. Again these estimates are based on the data of Xu et al. (19). The net effect is an increase of about 3000 kg CO_2e per year per 100 head of cattle.

This analysis is of some interest because it represents a likely, large-scale approach to the composting of animal byproducts in a feedlot environment. But comparing emissions that result from composting manure with and without byproducts was not the primary objective of this project. The comparison that is most pertinent to this work is between the impacts of two methods of handling the animal byproducts, rendering and composting. That comparison is made in Figures 1 and 2 in the main body of the report.

Appendix C: Cradle-to-Gate Analysis of GHG Emissions and Fossil Energy Use Associated with the Production of Soybean Meal and Oil
Brittany Sandy and Charles Gooding

Presentation and Analysis of Primary Data
The tables in this section resulted from calculations based on data developed and maintained by the U.S. Department of Energy's National Renewable Energy Laboratory (28). Much of the information in the NREL database came from a report commissioned by the United Soybean Board (USB) and prepared by Omni Tech International (23). NREL data were supplemented where necessary using other sources referenced below. To produce the USB report, Omni Tech updated an earlier cradle-to-gate analysis on the production of soybeans and the conversion of beans into meal and oil. The USB report was peer reviewed by international experts to verify that the work was conducted in accordance with ISO standards. The report was divided into sections on soy agriculture, soy crude oil and soy meal production (crushing), soy oil refining, and the production of the soy-derived feed stock methyl soyate (biodiesel). The analysis presented here stops with the production of soy crude oil and soy meal production, which are compared in this report to rendered fat and meal.

The first system in the cradle-to-gate analysis of soy oil and meal production is soybean agriculture. Data for agricultural processes were based on the U.S. soybean production practices in years 2001-2007. The functional unit was 1000 kg of soybeans. Table C1 reports the material and energy inputs. The NREL database was used to estimate CO_2, N_2O, CH_4, and CO_2e emissions and fossil energy consumption associated with each input. CO_2e emissions were calculated based on a global warming potential (GWP) of 25 and 298 for methane and nitrous oxide, respectively. GHG emissions and fossil energy consumption associated with agrochemicals used in soybean production were not included because they were not significant at the 0.1% level. Emissions and energy consumption associated with potash fertilizer are not reported in the NREL database so they were retrieved from a separate source (57).

The largest contributor to GHG emissions in soybean agriculture is the production of quick lime, which accounts for 66% of the total emissions produced from energy and material inputs.
In addition to material and energy inputs, the NREL database has data on two other GHG emission sources associated with soybean agriculture. Fertilizer application and water runoff result in the emission of 104 kg CO_2e/1000 kg beans in the form of N_2O. Transportation of material inputs to soybean agriculture contributes 0.4 kg CO_2e/1000 kg beans and uses 5.0 MJ of fossil energy/1000 kg beans.

Table C1 Soy agriculture inputs with related energy consumption and emissions per 1000 kg soybeans.

Inputs	Quantity per 1000 kg Soybeans	CO_2 Emissions [kg/1000 kg soybeans]	N_2O Emissions [kg/1000 kg soybeans]	CH_4 Emissions [kg/1000 kg soybeans]	CO_2e Emissions [kg/1000 kg soybeans]	Fossil Energy Consumption [MJ/1000 kg soybeans]
Energy Inputs						
Diesel (farm tractor) (l)	14.3	38.6	9.70E-04	1.92E-03	39.0	519
Electricity (MJ elec.)	25	4.55	7.51E-05	4.75E-05	4.57	52
Gasoline (farm tractor) (l)	4.5	9.41	2.75E-04	4.14E-03	9.58	146
LPG (MJ)	32	2.20	1.50E-04	3.33E-05	2.25	32
Natural Gas (MJ)	48	2.47	4.54E-05	4.54E-05	2.48	48
Material Inputs						
Agrochemicals (kg)	0.52	---	---	---	---	---
Nitrogen Fertilizer (kg)	1.6	1.04	7.06E-03	2.44E-03	3.2	57.2
Phosphorous Fertilizer (kg)	5.0	1.62	3.36E-05	3.14E-05	1.6	18.7
Potash Fertilizer (kg)	9.3	---	---	---	1.5	13
Quick Lime (kg)	94	123	6.11E-03	1.97E-03	124.6	535

Summing all contributions from the NREL database, the total consumption of fossil fuels resulting from soybean agriculture is 1430 MJ/1000 kg beans. The total emission of greenhouse gases is calculated to be 294 kg CO_2e/1000 kg beans. Based on a carbon content of 42.6% in soybeans, the uptake of CO_2 from the air as soybeans grow contributes -1560 kg CO_2e /1000 kg beans produced. When this is combined with the NREL emission results, net greenhouse emissions from soybean agriculture are -1266 kg CO_2e/1000 kg beans. The USB report estimates a net value of -1200 kg CO_2e/1000 kg beans.

After soybeans are grown, they are processed to produce crude soy oil and meal. For the USB report, the National Oilseed Processors Association (NOPA) collected and aggregated data, providing updates to data published in an earlier report issued by NREL (58). The data were updated because the 1998 study was based on a single soybean processing plant that was not representative of the soybean processing industry as a whole. The NOPA updates were obtained from data supplied by fifty soybean processing plants. The unit processes include soybean crushing and oil recovery via solvent extraction through crude oil degumming, and the data reflect full-facility energy and material input and outputs.

Table C2 reports emissions and fossil energy consumption associated with the production of 1,000 kg of crude soy oil and the co-product 4,131 kg of soy meal, which are produced simultaneously. For comparison some data from the 1998 study are shown beside the NOPA updates, but emissions and fossil energy consumption were based on the NOPA data. Biomass burned to produce heat during soybean processing is not included in the analysis because it does not contribute to net greenhouse gas emissions or to fossil energy consumption. Emissions and fossil energy consumption associated with hexane production were deemed to be negligible because nearly all of the hexane used in the solvent extraction process is recycled. Water effluents were also excluded because they have an insignificant effect on greenhouse gas emissions and energy consumption. Soybean hulls were assumed to be included in the meal. Table C3 shows that the largest contributors to GHG emissions and fossil energy consumption during soybean processing are burning of natural gas and coal to produce steam.

Table C3 combines all significant greenhouse gas emissions and fossil energy consumption related to soybean agriculture and soybean processing to produce crude, degummed soy oil and soy meal. It includes contributions from material and energy inputs and from transportation, as well as N_2O emissions from agricultural run-off. The denominator of each column is 1000 kg oil, but the numerator includes the total emissions or energy consumption required to produce 1000 kg of soy oil and the co-product, 4131 kg of soy meal. In the last two rows, emissions and fossil energy consumption are allocated on a mass basis according to the relative amounts of oil and meal produced.

Table C2 Greenhouse gas emissions and fossil energy consumption associated with processing of soybeans to produce 1000 kg of oil (and 4131 kg of soy meal as a co-product according to NOPA updates).

Inputs	**1998 NREL Study**	**NOPA Updates**	**CO_2 Emissions [kg/1000 kg soy oil]**	**N_2O Emissions [kg/1000 kg soy oil]**	**CH_4 Emissions [kg/1000 kg soy oil]**	**CO_2e Emissions [kg/1000 kg soy oil]**	**Fossil Energy Consumption [MJ/1000 kg soy oil]**
Energy Inputs							
Electricity (kWh)	410	289	189	3.13E-03	1.97E-03	190	2,180
Natural Gas (kcal)	1,569,000	---	---	---	---	---	---
Steam (kcal)	1,296,000						
% NG (NOPA)	---	65	232	8.18E-04	5.32E-04	232	4090
% #2 FO (NOPA)	---	0.5	2.40	1.16E-05	2.61E-06	2.40	31.5
% #6 FO (NOPA)	---	1	4.93	2.14E-05	1.95E-04	4.94	63.0
% Coal (NOPA)	---	32	181	3.83E-03	0.0342	183	2013
% Biomass (NOPA)	---	1	---	---	---	---	---
% LF gas (NOPA)	---	0.5	1.78	6.29E-06	4.09E-06	1.78	31.5
Total kcal of heat	*2,865,000*	*1,502,729*					
Material Inputs							
Soybeans (kg)	5,891	5,236	958	0.0770	0.0556	983	7470
Hexane (kg)	11.9	2.96	---	---	---	---	---
Water (kg)	19.4	2,547	---	---	---	---	---
Outputs							
Products (kg)							
Soy Meal Produced (% by mass)	4,478 (82%)	4,131 (80.5%)	1,263	0.0683	0.0745	1,286	12,758
Soybean Oil Produced (% by mass)	1000 (18%)	1000 (19.5%)	306	0.0165	0.0180	311	3,090

Table C3 Total emissions and fossil energy consumption to produce 1000 kg soy oil and 4131 kg of soy meal co-product.

Input	CO_2 Emissions [kg/1000 kg oil]	N_2O Emissions [kg/1000 kg oil]	CH_4 Emissions [kg/1000 kg oil]	CO_2e Emissions [kg/1000 kg oil]	Fossil Energy Consumption [MJ/1000 kg oil]
Agriculture					
Material Inputs	658	0.0691	0.0233	681	3267
Transportation	2.10	5.22E-05	1.22E-04	2.10	26
Electricity	23.8	3.93E-04	2.49E-04	23.9	272
Other Energy	276	7.54E-03	0.0321	279	3,901
Output N2O Emissions	---	1.83	---	546	---
Carbon sequestered in beans (42.6% C)	-8,174	---	---	-8,174	---
TOTAL FOR AGRICULTURE	-7,214 (960)	1.91	0.0558	-6,642 (1,532)	7,470
Soybean Processing					
Material Inputs (Soybeans)	-7,214 (960)	1.91	0.0558	-6,642 (1,532)	7,470
Transportation	135	3.36E-03	3.66E-03	136	1,670
Electricity	189	3.13E-03	1.97E-03	190	1,040
Energy (Heat Inputs)	422	4.69E-03	0.0349	424	6,230
TOTAL AGRICULTURE PLUS PROCESSING	-6,468 (1,706)	1.92	0.0963	-5,892 (2,282)	16,410
Product Allocation					
TOTAL FOR 1000 kg SOY OIL (19.5%)	-2,489 (333)	0.374	0.0188	-2,377 (445)	3,200
TOTAL FOR 4131 kg SOY MEAL (80.5%)	-3,986 (1,373)	1.55	0.0775	-3,522 (1,837)	13,210

Note: Values in parentheses represent emissions without credit for carbon sequestration.

In Table C3 transportation-related GHG emissions and fossil fuel consumption were derived from data in the NREL database. The USB report stated only that agricultural materials are transported an average of 300 miles and beans an average of 75 miles, each by truck. The NREL database reports transportation of material inputs to agriculture sites in units of t*km for diesel-powered truck transportation and for train transportation. The values are 0.0220 t*km/1000 kg beans and 20.9 t*km/1000 kg beans, respectively. The total CO_2e emissions associated with transportation using the NREL values are 0.4 kg CO_2e/1000 kg beans (2.10 kg CO_2e/1000 kg oil). This represents a small portion of the total greenhouse gas emissions. The fossil energy consumption associated with agriculture transportation is 4.95 MJ/1000 kg beans (25.9 MJ/1000 kg oil). The NREL reported 1,690 t*km to transport soybeans to the crushing facility by diesel-powered truck. This accounts for 136 kg CO_2e emissions/1000 kg soy oil and 1,670 MJ/1000 kg oil of fossil energy consumption.

In a cradle-to-gate study that begins with the growth of soybeans and ends with production of soy oil and meal, it is appropriate to take credit for carbon that has been extracted from CO_2 in the air and sequestered in the products. Table C3 includes negative GHG emissions that resulted from sequestration. The values reported are based on the assumption that soybeans are 42.6% carbon. Beneath the row where sequestration is first introduced, some blocks in the table contain two numbers. Positive numbers in parentheses are gross emissions, neglecting sequestration. Negative numbers are net emissions after sequestered carbon dioxide has been subtracted.

The USB report contains a contradiction in the mass balance used to allocate carbon between soy oil and soy meal. The USB reports that the carbon content of soybeans is 42.6%, the carbon content of soybean oil is 77%, and the carbon content of soybean meal is 48%. Applying these percentages to the NOPA mass flow rates in Table 2 would mean that 2231 kg of carbon enters the processing step in the 5236 kg of beans, but 2753 kg of carbon leaves in the 1000 kg of oil and 4131 kg of meal. Apparently the 48% reported by the USB actually refers to the percentage of protein in soy meal rather than the percentage carbon in soy meal. If the percentages of carbon in beans and oil and the relative amounts of oil and meal produced are correct, a mass balance on carbon indicates that meal must contain 35.4% carbon. In the last two rows of Table C3, emissions and fossil fuel use are allocated between oil and meal on a total mass basis (19.5% to oil, 80.5% to meal). The sequestration credit is allocated according to the amount of carbon in each product as calculated from the mass balance.

Comparison to Other Studies

Miller and Theis (59) used three established life cycle inventories of agricultural operations to generate emission data for the production of soybeans and for soybean processing. They concluded that the GREET model (Greenhouse gases Regulated Emissions and Energy use in Transportation) is the most reliable because the assumptions and boundaries are transparent, and the data are obtained from the US Environmental Protections Agency's AP-42 documents. Miller and Theis report total emissions from soybean agriculture to be 1,426 kg CO2e/1000 kg soy oil, which is 106 kg CO2e/1000 kg soy oil or 6.9% lower than the 1,532 kg CO2e/1000 kg soy oil shown in Table C3, neglecting carbon sequestration. The GREET model does not include quick lime production, which accounts for 652 kg CO2e/1000 kg soy oil of the emissions calculated in the USB report, or almost half of the difference between the GREET and USB results.

Soybean-processing emissions obtained from the GREET model in the Miller and Theis paper (60) differ somewhat from those in the USB report (23). Miller and Theis allocated processing emissions to soy oil and soy meal based on relative mass productions of 18% and 82%, respectively, which resulted in 219 kg CO2e emissions/1000 kg of soy oil allocated to the production of soy oil. This does not include the material input of soybeans. The USB estimates shown in Table C3 are lower. Without the emissions associated with the material input of soybeans, the allocated emissions from soybean processing (using mass allocation of 19.5% for soy oil) are 146 kg CO2e/1000 kg soy oil.

Li and coworkers (60) report total energy consumption, potential energy recovery, and net energy use for various steps in soybean processing, but do not report values for soybean agriculture. The energy consumption value most apt for comparison to the USB report was 6,080 MJ of fossil energy consumption/1000 kg soy oil for soybean processing. This value included energy consumption during pre-processing of soybeans, hexane solvent extraction, post-processing, and the hexane supply chain. The USB analysis (23) indicates that energy consumption for soybean processing, neglecting the inputs from the agriculture process, is 8,940 MJ/1000 kg soy oil. This value is higher than the number reported by Li et al. even though they included the hexane supply chain, which was deemed to be negligible in the USB calculations. The exclusion of transportation in the Li report accounts for a difference of 1,670 MJ/1000 kg soy oil between their work and the USB data, but the remaining 1,190 MJ/1000 kg oil difference cannot be clearly reconciled with the information given.

Miller and coworkers published another paper entitled "A Comparative Life Cycle Assessment of Petroleum and Soybean-Based Lubricants" (61). Similar to the previous paper by Miller and Theis (59), three databases and their underlying assumptions were evaluated to establish an inventory. The GREET model was chosen again as the preferred method because of its transparency of boundaries and user assumptions. Processes included in reported emissions were farming, fertilizer production and transportation, upstream production and transportation of lime and pesticides, in-field emissions, transportation to processing plant, soybean processing, and transportation to production facility. The study reports emissions of 400 kg CO_2, 0.69 kg N_20, and 0.65 kg CH_4 per 1000 kg of oil produced. It also concludes that 2,440 kg CO2/1000 kg soy oil is sequestered by the soybeans. The sequestration value is consistent with the assumption that soy oil contains 66% carbon, whereas the USB report uses a soy oil carbon content of 77%. Using a global warming potential of 25 and 298 for methane and nitrous oxide, respectively, and ignoring carbon sequestration, Miller's 2007 data translate into emissions of 620 kg CO_2e/1000 kg oil. Miller reports a total of 4,300 kg CO_2e emissions from the production of 1,000 kg of soy oil and the soy meal co-product. This number is nearly twice the USB total of 2,282 kg CO_2e emissions/1000 kg oil, neglecting carbon sequestration. A primary reason for the discrepancy is that the Miller results were based on the 1998 biodiesel study, and NOPA updates were used to generate emission values in the USB report.

Another study published by Kim and Dale (62) examined emissions associated with two bio based products, ethanol and soybean oil, with feedstocks produced in various Midwestern farming locations. Biomass production (agriculture), bio refinery (soybean preparation, oil extraction, meal processing, solvent recovery, oil recovery, and oil degumming process), and upstream processes (energy and chemicals) were included in this study. Forty counties in the Midwest were chosen as bio refinery locations and farming sites, and cradle-to-gate GHG emissions associated with ethanol and soybean oil production were estimated. The DAYCENT model was used to estimate carbon sequestration by soil and N_20 emissions from soil, but the assumptions of this model were not reported. The results of the study indicate total emissions of 1,200 kg CO_2e per 1000 kg soy oil from agriculture and the production of soy oil. Curiously the paper reports that carbon sequestration is responsible for only 2.5% of the net emissions associated with soybean oil production whereas the USB study reports that carbon sequestration has a much larger influence. Since the percentage of carbon sequestration reported in this study is so small, the total emission results are more comparable to the total emissions for the production of soy oil from the USB report, neglecting carbon sequestration (2,282 kg CO2e/1000 kg soy oil). Some of the difference exists because Kim and Dale neglected emissions related to transportation, but clearly the major difference in comparison to the USB report is the treatment of carbon sequestration. Upon inquiry the authors replied (63) that "We did not account for carbon in soybean oil because its lifetime is very short." This answer seems to contradict the cradle-to-gate boundary of the study so the discrepancy remains unresolved.

Appendix D: Energy Use and Greenhouse Gas Emissions Associated with Meat Production Benjamin Childs and Charles Gooding

Numerous recent studies have attempted to quantify the energy and environmental impacts of various meat production systems. This review examines beef production first, followed by poultry and swine. Slaughterhouse energy use and GHG emissions are considered separately from agricultural operations. The studies cited did not consistently distinguish among types and sources of energy so all energy is assumed to be from fossil sources unless stated otherwise.

Beef Production

Pelletier and his associates collected data and compared life cycle environmental impacts of three beef production strategies practiced in the Upper Midwest of the United States (25). The comparison was based on a hypothetical herd consisting of 100 cows, 15 heifers, and 3 bulls. In the first year this herd was farm raised and fed a diet of pasture grass and mixed grass and hay with a small wheat supplement. Ninety calves were born and raised to a weight of 216 kg. At the end of the year 15 cows and 1 bull were sent to slaughter, 15 calves were retained in the herd as heifers, 75 calves were sent to a finishing system, and a new bull was added to the herd. The model herd diverges after the first year to consider three alternative finishing systems, each with a defined feeding regime:

- Feedlot: 303 days finishing to achieve an average weight of 637 kg
- Backgrounding/feedlot: 300 days on pasture followed by 150 days in a feed lot, finishing at 637 kg
- Weaned to pasture: 450 days on a ration of forage and hay, finishing at 505 kg.

Each of the first two alternatives accounts for nearly 50% of beef production in the Upper Midwest. Pasture weaning serves small markets and accounts for less than 1% of total production. Pelletier et al. reported cumulative energy consumption for each alternative without distinguishing types or sources of energy, and they reported greenhouse gas emissions in terms of carbon dioxide equivalents. They also reported results for two environmental impacts that are beyond the scope of this study, eutrophying emissions and ecological footprint. Data on energy use and GHG emissions are summarized in Table D1 below. These results were taken directly from Pelletier's Tables 3 and 4, but they have been converted to a basis of 1 kg of live weight beef delivered to a slaughterhouse. In Figure 1 of the Pelletier paper, pasture weaning is shown to result in higher energy use and higher GHG emissions than either of the more widely practiced finishing procedures, but this conclusion could not be reconciled with other data reported in the paper. Table D1, which is based on direct translation of the data reported in Pelletier's Tables 3 and 4, indicates that the GHG emissions of pasture weaning are indeed higher than emissions from finishing beef solely in a feedlot or backgrounding before finishing in a feedlot, but energy use for pasture weaning falls between the other two alternatives.

Table D1. Energy use and GHG emissions per kg of live beef delivered to slaughter [calculated from results reported by Pelletier et al.(25)]

	energy use (MJ/kg)	GHG emissions (kg CO_2e/kg)
First year on farm	**25.8**	**10.3**
feed production, %	93	32.9

enteric methane, %	0	43.4
manure[a] , %	0	21.1
other[b] ,%	7	2.6
<u>**Finishing Alternative**</u>		
Feedlot 303 days	**12.3**	**4.5**
feed production, %	85.6	26.7
enteric methane, %	0	40.2
manure[c] , %	0.6	30.4
other[d] ,%	13.8	2.7
Backgrounding		
plus Feedlot 450 days	**19.1**	**5.9**
Backgrounding (300 days)		
feed production, %	45.0	20.4
enteric methane, %	0	20.6
manure[a] , %	0	12.7
other[d] ,%	6.9	1.6
Feedlot (150 days)		
feed production, %	43.4	16.0
enteric methane, %	0	11.4
manure[a] , %	0.2	16.4
other[d] ,%	4.5	0.9
Pasture 450 days	**16.2**	**6.4**
feed production, %	93.7	36.6
enteric methane, %	0	41.5
manure[a] , %	0	20.9
other[d] ,%	6.3	1.0

[a] predominately nitrous oxide, but also includes methane

[b] predominately legacy cost of producing bull

[c] includes N_2O and CH_4 emissions and energy inputs/emissions of manure handling

[d] includes transport of calves

A similar study on beef production in western Canada was published by Beauchemin et al. (26) in the same issue and journal as Pelletier's work. Beauchemin modeled the farm plus feedlot scenario and estimated total GHG emissions to be 13.0 kg CO_2e/kg finished live weight. For comparison the paper cites an independent study conducted in the US in 2003, which produced essentially the same result, and a review published in 2009 that indicated a range of 10 to 22 kg CO_2e emissions/kg finished live weight. Pelletier's estimate for the farm plus feedlot scenario shown in Table D1 is 14.8 kg CO_2e/kg finished live weight.

Beauchemin estimated the typical breakdown of GHG emissions expressed as carbon dioxide equivalents to be 63% due to enteric methane, 23% from nitrous oxide from manure, 5% due to methane from manure, 4% from nitrous oxide from soil, and 5% from burning fuel for energy use. Pelletier's emission breakdown in Table D1 is categorized somewhat differently, and his reported fraction of emissions due to enteric methane is substantial, but not dominant. Upon close study it appears that Beauchemin's LCA ignores energy use and emissions associated with feed production. Energy use was reported by Beauchemin only in terms of the resulting GHG emissions. Applying an emission factor for either natural gas or diesel fuel to the emission results yields an estimate for energy use between 8 and 12 MJ/kg live finished beef, compared to Pelletier's estimate of 38 MJ/kg live finished beef as shown in Table D1. Feed production is the dominant contributor to Pelletier's estimate for energy use, and it accounts for about 30% of his estimate of GHG emissions. Lopez, Mullins, and Bruce (27) also state that production of feed is the largest consumer of energy in beef production. Their estimate of 18 GJ per head translates into 21 MJ/ kg of live finished cattle.

A recent review paper by de Vries and de Boer (8) compared and contrasted life cycle assessments conducted between 1997 and 2008 on several livestock products. All studies examined were based on practices in member countries of the Organization for Economic Cooperation and Development. Three studies examined beef production in Ireland, Sweden, and the UK, and concluded that energy use ranges from 34 to 52 MJ/kg of product, which translates into 15 to 22 MJ/kg of finished live weight using de Vries and de Boer's estimates of yield. Estimates of GHG emissions ranged from 14 to 31 kg CO_2e/kg product or 6 to 14 kg CO_2e/kg finished live weight.

Poultry Production

Two studies cited by de Vries and de Boer (8) examined poultry production in France and the UK. These indicate that energy use ranges from 15 to 29 MJ/kg of product or 8 to 16 MJ/kg live weight. GHG emissions ranged from 3.7 to 6.9 kg CO_2e/kg product or 2 to 4 kg CO_2e/kg live weight. Lopez et al. (27) estimated total energy for poultry farming in the US to be 11 MJ/kg live weight, which is consistent with the work reviewed by de Vries and de Boer.

Pork Production

Five studies reviewed by de Vries and de Boer (8) examined swine operations in France, the Netherlands, Sweden, and the UK. Estimates of energy use ranged from 18 to 34 MJ/kg product or 10 to 18 MJ/kg live weight. GHG emissions ranged from 3.9 to 10 kg CO_2e/kg product or 2 to 5 kg CO_2e/kg live weight.

Slaughterhouse Operations

Slaughterhouses typically burn fossil fuels to produce steam or direct heat for meat processing, and they use purchased electricity for cooling and refrigeration. Citing material from primary sources, Lopez et al. (27) estimate total energy use at 1.5 to 5.3 MJ/kg of meat product, which translates into 1 to 3 MJ/kg live weight of animals entering the slaughterhouse. If the coal emission factor (worst case) is applied to the upper limit of this energy estimate, the resulting GHG emission estimate is only 0.3 kg CO_2e/kg live weight. Hence both energy use and GHG emissions associated with slaughterhouse operations are quite small compared to the impacts of the agricultural operations that produced the animals.

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