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Abstract

Beef production, especially when based on the calves from suckler cows, typically has the greatest environmental impacts among various livestock production systems. Conventional beef production in Japan uses a large amount of imported concentrate feed, which results in substantial environmental impacts. Yakumo Farm, located in northern Japan, produces grass-fed beef using only farm-grown feed. Pesticides and chemical fertilizer were used in the past, but organic management was introduced at the farm more recently. We assessed the environmental impacts of grass-fed beef production at Yakumo Farm before and after the introduction of organic management (hereafter, non-organic and organic, respectively), and a conventional Japanese (hereafter, conventional) system using life-cycle assessment (LCA). We constructed the LCA models based on data collected at Yakumo Farm, from the literature and from LCA databases. The LCA system boundaries included feed production, transportation, processing, animal management, enteric fermentation, and manure and its management. The functional unit was defined as 1 kg of cold carcass weight of beef steers. The impact of each system was determined regarding its potential contribution to global warming, acidification, and eutrophication, as well as its energy consumption. Both the organic and non-organic systems had much smaller impacts on acidification, eutrophication, and energy consumption than the conventional system. The impact on global warming associated with the organic system was equivalent to the conventional system, whereas for the non-organic system it was greater than for the conventional system. Generally, the exclusion of the process of feed transportation reduced the environmental impacts. The use of chemical fertilizer increased the global warming-related impact in the non-organic system. Therefore, we concluded that introducing organic management to Yakumo Farm mitigated its environmental impacts. Our results provide implications for

mitigating the environmental impacts caused by beef or other livestock production not only in Japan, but also in other countries depending upon imported feed.

Keywords: Beef production, Environmental impact, Feed transportation, Life-cycle assessment, Livestock production, Organic farming

1. Introduction

Sustainability of food production has attracted much attention in recent decades. In general, livestock products bear greater environmental burdens than food of plant origin (excluding greenhouse crop production, for example) (Mogensen et al., 2009; Schmidinger and Stehfest, 2012). de Vries and de Boer (2010) compared the environmental impacts of several livestock products, and reported that beef production used the most land and energy, and had the greatest global warming potential (GWP). It was also found that beef production systems based on the calves from suckler cows had greater environmental impacts than those based on dairy calves (de Vries et al., 2015). Nguyen et al. (2010) evaluated the environmental impacts of the EU suckler-based beef production system and compared them with those of the conventional Japanese system (Ogino et al., 2004, 2007). They reported that these systems had similar levels of GWP, but that the Japanese system had greater acidification and eutrophication potentials, and used much more energy. Peters et al. (2010) compared the GWP and energy use among beef production systems in Australia and other countries including Japan. According to their comparisons, Japanese beef production had the greatest GWP and used, by far, the most energy. Other research also indicated the considerable GWP (Stackhouse-Lawson et al., 2012) and energy consumption (Ogino et al., 2016) of Japanese beef production. Thus, beef produced in Japan can be regarded as a food with a great environmental load.

Suckler-based beef production in Japan is divided into the cow-calf and fattening (backgrounding and finishing) stages. In the conventional beef production system in Japan, the fattening stage has greater GWP than the cow-calf stage (Ogino et al., 2004, 2007), which contrasts with systems in the USA (Lupo et al., 2013; Pelletier et al., 2010; Stackhouse-Lawson et al., 2012), Canada (Beauchemin et al., 2011), and Uruguay (Picasso et al., 2014). Japanese beef production typically uses a non-grazing housing system that relies largely on concentrate feed especially during the fattening stage. Most concentrate feed used in Japanese livestock production (88% in 2013, based on total digestible nutrient) is imported from other countries, mainly the USA, although most roughage (77%) is produced within Japan. Hence, the environmental impacts of Japanese beef production are enhanced not only by production of a large amount of concentrate feed but also by feed transportation.

Life-cycle assessment (LCA) is a widely accepted method for evaluating and comparing the environmental impacts of livestock production systems (de Vries and de Boer, 2010). Numerous comparative LCAs among different beef production systems have been conducted to assess the mitigation of environmental impacts (reviewed by de Vries et al., 2015). de Vries et al. (2015) compared the environmental impacts of beef produced in contrasting systems in terms of the type of diet fed to fattening calves (roughage- or concentrate-based) and the type of production (organic or non-organic). They reported smaller GWP and energy consumption for concentrate-based systems compared with roughage-based systems, whereas no clear patterns were found in their acidification and eutrophication potentials. In addition to this, GWP and energy consumption were smaller in organic systems than in non-organic systems, but organic systems had greater acidification and eutrophication potentials.

Yakumo Experimental Farm, Field Science Center, Kitasato University School of Veterinary Medicine (Yakumo Farm, hereafter) is located in southwest Hokkaido in northern Japan (42°15'N, 140°8'E). Yakumo Farm produces grass-fed beef using only farm-grown feed, which is distributed as "Kitasato Yakumo Beef" (hereafter, Yakumo Beef). Yakumo Farm had used pesticides and chemical fertilizer until 2002 and 2004, respectively. Since 2005, the farm has been managed organically. Subsequently, Yakumo Beef was certified as Japan’s first organic beef. Yakumo Beef has few environmental impacts from feed transportation (only within the farm), in contrast to beef produced using the conventional Japanese system, which is based on concentrate feed that is transported long distances, such as from the USA to Japan. Large amounts of carbon dioxide, sulfur oxides and nitrogen oxides are emitted and energy is used to a large degree in the process of feed transportation (Table S1). Therefore, it is hypothesized that Yakumo Beef has smaller GWP, acidification and eutrophication potentials, as well as less energy consumption than conventionally produced beef, in contrast to the conclusions derived by de Vries et al. (2015). However, like other grass-fed beef production systems (Capper, 2012; Lupo et al., 2013; Pelletier et al., 2010), production efficiency (body weight gain) at Yakumo Farm is lower than that of the conventional system (Table 1), which might enhance the environmental impacts per product weight, as reported in previous studies (Beauchemin et al., 2011; Lupo et al., 2013; Pelletier et al., 2010).

In this study, we used LCA to evaluate the environmental impacts of grass-fed beef produced at Yakumo Farm before and after the introduction of organic management (hereafter, non-organic and organic, respectively), and compared the results with those for the conventional Japanese (hereafter, conventional) system.

2. Materials and methods

2.1. Goal and scope definition

The targets of this analysis were steers. The varieties of cattle were Japanese Shorthorn and its crossbreeds at Yakumo Farm, and Japanese Brown in the conventional system whose market weight has been similar to that of Yakumo Beef in recent years. Note that the targeted varieties of cattle are different from the Japanese Black variety. The environmental impacts of Japanese

Black beef production have already been assessed in several studies (Ogino et al., 2004, 2007; Oishi et al., 2013; Tsutsumi et al., 2014). Although the environmental impacts of conventional production of Japanese Brown beef were assessed by Tsutsumi et al. (2017), the methods of calculation are slightly different from those employed in this study. In the current study, the functional unit was defined as 1 kg of cold carcass steer weight.

The data for the production systems (including the cattle growth curve, grazing schedule, resources used for pasturing, forage nutrient values and reproductive performance) of Yakumo Farm were obtained for 1997–2004 for the non-organic system and 2006–2013 for the organic system. The data for the conventional system were obtained from Nihon Akaushi Touroku Kyoukai (2000), NARO (2009, 2010) and the Agriculture and Livestock Industries Corporation (2016). The system boundaries included feed production, feed processing, feed transportation, animal management, enteric fermentation, and excreta and its management. All resources used in the system were considered, such as the energy used to produce the chemical fertilizer; however, capital goods, such as barns and machinery, were not considered.

2.2. Production systems of Yakumo Farm

In the organic and non-organic systems at Yakumo Farm, the following issues were common. All cattle were grazed on pastures from mid-May to mid-October without supplemental feed, and managed in barns during the remaining period (Tables 1 and 2). In the barns, the cattle were fed farm-grown roughage. The lactating period was six months.

There were no differences in age at first calving and calving interval between the organic and non-organic systems, whereas calving occurrences per cow in the non-organic system were higher than those in the organic system. Both grass silage and hay were used as roughage in the non-organic system, but only grass silage was used in the organic system. The fattening period was longer and both live weight at slaughter and carcass weight were heavier in the organic system than the non-organic system. The fattening period has been gradually extended since 2003 based on a management decision.

In the non-organic system, chemical fertilizer was applied onto the pastures used for both harvesting (Table S2) and grazing (Table S3). To obtain 1 t of dry matter (DM) of roughage, 12.4 kg of nitrogen (N), 10.0 kg of phosphate (P_2O_5), and 18.3 kg of potassium (K_2O) were used. In addition, 8.7 kg of magnesium (MgO), 12.7 kg of fused magnesium phosphate, 44.3 kg of magnesia lime, 3170 kg of manure and 89.9 kg of other organic fertilizer were applied. To produce 1 t DM of roughage in the organic system, 3007 kg of manure and 21.7 kg of other organic fertilizer were applied.

We estimated the herbage intake based on the required total digestible nutrients (TDN) (NARO, 2009). NARO (2009) stated that the energy needed for the maintenance of cattle on a sloping pasture is 25% higher than their maintenance energy in a feedlot. We determined the required TDN based on this assumption. We estimated the milk intake by calves based on NARO (2009).

2.3. Conventional beef production system

In the conventional system, all cattle were managed in barns during all seasons. The cattle were fed concentrate mixture, grass hay and rice straw (Table 2). The lactating period was three months. Compared with Yakumo Farm, the age of first calving was earlier but the calving interval was longer in the conventional system. The steers were fattened to 761 days of age (722 kg in body weight and 465 kg in cold carcass weight). The milk intake by calves was estimated based on NARO (2009).

2.4. Life-cycle inventories

In the following analysis, we used MiLCA software, which was specifically designed to conduct LCA by the Japan Environmental Management Association for Industry (JEMAI, 2012). We took into account the energy consumption and emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3), nitrogen dioxide (NO_2), nitrogen oxide (NO_x), sulfur dioxide (SO_2) and sulfur oxide (SO_x). To construct the life-cycle inventories, we used the Inventory Database for Environmental Analysis (IDEA) via MiLCA.

Resource consumption data for feed production and processing were based on the records of Yakumo Farm and previous studies (Kim et al., 2014; Kobayashi and Yuyama, 2006; NIAES, 2003; Pelletier et al., 2010; Pradhan et al., 2011). In the conventional system, all concentrate feed and grass hay for calves was produced in the USA, whereas the other roughage used was farm-grown (Table 2). Evaluations of the direct emissions from soil were carried out based on the literature listed in Table 3 (Bouwman et al., 2002; GIO, 2016; Hayashi et al., 2011, 2009, 2008; IPCC, 2006; Shimizu et al., 2013). Tables S3–S5 provide the life cycle inventories for all feed production used in our analysis.

The enteric CH_4 emissions were estimated according to age for calves under five months (Sekine et al., 1986), or DM intake for other cattle (Shibata et al., 1993), as described in Table 4. Both in Yakumo Farm and the conventional systems, composting was carried out by piling without forced aeration, a method employed at most Japanese beef farms (GIO, 2016). The amounts of excreted organic matter and N were estimated according to IPCC (2006) and Terada et al. (1998), respectively. Based on these sources and the literature listed in Table 4 (Bouwman et al., 2002; GIO, 2016; Groot Koerkamp et al., 1998; Shiraishi et al., 2004), the emissions of CH_4, NH_3, and N_2O from excreta and its treatment were estimated.

We also accounted for the environmental loads associated with animal management including lighting of the cattle barn, feed preparation, and carrying manure within the farm according to the Agriculture, Forestry and Fisheries Technology Information Society (AFFTIS, 2000).

2.6. Allocation of environmental impacts

We allocated the environmental impacts of by-product feeds according to their prices, where the ratio of allocated environmental impacts per unit weight was the same as the ratio of their prices. We conducted this allocation assuming that (1) unhulled rice and rice straw yielded 600 and 750 kg/ha, respectively, and the ratio of prices was 25:2 for unhulled rice to rice straw; (2) 780 kg of flour and 220 kg of bran were made from 1000 kg of wheat, and the ratio of prices was 81:19 for flour to bran; and (3) 205 kg of soybean oil and 795 kg of soybean meal were made from 1000 kg of soybean, and the ratio of prices was 72:28 for soybean oil to soybean meal.

2.7. Transportation

We calculated the environmental loads of transporting the feed produced in the USA as follows (see Table S1). Grass hay, alfalfa hay, maize and soybean meal were transported to the port of New Orleans by truck (50 km) and by freighter ship along the Mississippi River (1385 km). Wheat bran was transported to the port of Portland by truck (50 km) and rail (2765 km). The marine transportation distances from New Orleans and Portland to Japan (the port of Tomakomai) were 18053 and 8997 km, respectively (Japan Coast Guard, 2011). The land transportation distance by truck within Japan was 210 km.

2.8. Life-cycle impact assessment

Four impact categories (global warming, acidification, eutrophication and energy consumption) were adopted for the impact assessment of this study. We calculated the GWP for a 100-year time horizon (for CO_2: 1, CH_4: 25 and N_2O: 298; IPCC, 2007), the acidification potential (AP for SO_2 and SO_x: 1.00, NH_3: 1.88, and NO_2 and NO_x: 0.70; Heijungs et al., 1992) and the eutrophication potential (EP for NH_3: 0.35, and NO_2 and NO_x: 0.13; Heijungs et al., 1992).

3. Results

3.1 Global warming potential

The non-organic systems had the greatest GWP, and there was little difference between GWPs for the conventional and organic systems (Table 5). The top contributor to the total GWP for all three systems was enteric fermentation, but the subsequent contributors differed among the systems. Excreta (including composting) was the second strongest contributor in the organic system, whereas in the non-organic system it was roughage production. Feed transportation was the second largest contributor in the conventional system, followed by concentrate production. The GWPs caused by each process of animal management, enteric fermentation and excreta in the non-organic system were equivalent to those in the organic system. However, the GWPs caused by feed production were different between the organic and non-organic systems, which was reflected in the difference between the total GWPs. Because a large amount of CO_2 is emitted during the production of chemical fertilizers (Tables S3 and S4), the use of chemical fertilizer increased GWP in the non-organic system.

3.2 Acidification and eutrophication potentials

The conventional system had the greatest AP, which was about three times as high as the corresponding values in the organic and non-organic systems (Table 6). In the conventional system, the top contributor was feed transportation followed by excreta and concentrate feed production. Excreta contributed the most to total AP in the organic and non-organic systems. AP caused by feed production was smaller in the organic than in the non-organic system, whereas AP caused by excreta was smaller in the latter, resulting in smaller AP in the non-organic system than in the organic system. The EP results were similar to those of the AP results (Table 7). The conventional system had the greatest EP, with values about twice those of the organic and non-organic systems. The top and subsequent contributors to EP in each production system were the same as those for AP. The EP was smaller in the non-organic system than in the organic system for the same reason as mentioned above for AP.

3.3 Energy consumption

The conventional system had by far the greatest energy consumption, which was 553% and 61% greater than the values for the organic and non-organic systems, respectively (Table 8). In the conventional system, feed transportation was the top contributor followed by concentrate production. Roughage production contributed the most to total energy consumption in the non-organic and organic systems. Energy consumption of feed production in the non-organic system was 365% greater than that of the organic system. This difference was caused by the use or non-use of chemical fertilizer (see Tables S3 and S4) and, similar to GWP, it was reflected in the difference in total energy consumption.

4. Discussion

4.1. Testing the hypothesis

The organic and non-organic systems had smaller AP, EP, and energy consumption than the conventional system (Tables 6–8). Although the organic system exhibited a slightly greater GWP than the conventional system (Table 5), the difference was insignificant as the order could be changed depending on the methodological choices. For example, we recalculated the GWP for the feed transportation process except for transportation within Japan using other emission factors (EPA, 2014). Consequently, the GWP for feed transportation in the conventional system was estimated as 7.5 kg CO_2e per carcass weight, and then the total GWP was calculated as 29.4 kg CO_2e whereas it was 29.3 kg CO_2e in the organic system. The non-organic system had a greater GWP than the conventional system. Overall, these results support the hypothesis that Yakumo Beef has smaller environmental impacts than conventionally produced Japanese beef. In the conventional system, the process of feed transportation was the top contributor to all the environmental categories assessed. Without the process of feed transportation, GWP in the conventional system would be the smallest, and its AP and EP would lie between those of the organic and non-organic systems. Therefore, if the environmental impacts caused from feed transportation are not taken into account, a comparison of the results for GWP, AP and EP between Yakumo Farm and the conventional system would support the conclusions of de Vries et al. (2015). However, in the present circumstances, it is not feasible to increase production of concentrate feed within Japan.

Even if the process of feed transportation is ignored, the conventional system has a greater energy consumption than the organic system, in contrast to the result by de Vries et al. (2015). This is because of the large amount of concentrate used in conventional Japanese beef production (cf. production in the EU; Nguyen et al., 2010, for example). The process of concentrate production accounted for 33% of the energy used in the conventional system and, similarly, feed transportation accounted for 51% (Table 8). Chemical fertilizer production was the top contributor to the energy consumption in the process of concentrate production (Table S5). Therefore, to reduce the energy consumption in Japanese beef production, it is necessary to reduce not only the amount of imported feed but also the amount of chemical fertilizer used for feed production. To mitigate the environmental impacts, introduction of a beef production system based on roughage without chemical fertilizer use, such as that at Yakumo Farm in recent years, or with a reduced usage level, is a feasible option in Japan or other countries that depend on imported concentrate feed such as South Korea or the United Arab Emirates.

4.2. Effects of the introduction of organic management

The GWP and energy consumption were smaller in the organic system than in the non-organic system (Tables 5 and 8). Only in the process of feed production were GWP and energy consumption different between the organic and non-organic systems. The fattening period was longer in the organic system than in the non-organic system, which enhanced emissions of CH_4 from enteric fermentation and N_2O from excreta for production of one steer although these differences were not reflected in the emissions per carcass weight. The non-organic system used chemical fertilizer (Tables S2 and S3), which raised the productivity of feed per unit area, when compared with the organic system. However, its livestock productivity (reproduction rate and weight gain) was not much higher than that of the organic system (Table 1), which led to greater GWP and energy consumption per unit of beef in the non-organic system. The AP and EP were slightly greater in the organic than in the non-organic system (Tables 6 and 7). This was mainly because of the extension of the fattening period, which increased NH_3 emissions from excreta and composting (Table 1; see Ogino et al., 2004), rather than the introduction of organic management.

Masuda and Yamamoto (2013) performed LCA for organic and conventional roughage production in Japan, and reported that organic grass production had smaller GWP, AP and EP but greater energy consumption. Their conclusion for energy consumption is contrary to our analysis (Table S2). In our study, energy consumption of grass production (harvesting) in the organic system was 1.21 GJ per 1 t DM, whereas it was 5.32 GJ per 1 t DM in the non-organic system. The inconsistency was presumably because they used an input-output analysis to calculate the indirect energy consumption, whereas we used a process analysis.

It has been reported that the effects of introducing organic management into beef production on the environmental impacts differ depending on the environmental categories and production systems assessed (de Vries et al., 2015; Meier et al., 2015). The previous comparisons were made among farms with organic or non-organic management. This study is the first work to assess the environmental impacts of beef production for the same farm before and after the introduction of organic management. Our analysis has the advantage of having little dependence on the variability in land productivity and livestock performance of the farm.

The results indicate that introducing organic management at Yakumo Farm has yielded beneficial effects on the environment. Hojito et al. (2016) assessed N flow at Yakumo Farm under organic management. They showed that the soil N stock increased gradually and N export was low, and concluded that it is possible to balance N inputs with N outputs in beef production without the need for feed or fertilizer imports. Currently, Yakumo Beef trades at prices as high as premium beef from Japanese Black, which is known for its highly marbled meat. This high price might be attributed to not only the quality of the meat, but also its environmental performance. Therefore, beef production at Yakumo Farm under organic management can be considered economically and environmentally sustainable.

Land use is also a crucial determiner of the sustainability of livestock production (de Vries and de Boer, 2010). At Yakumo Farm, grass yield decreased after the introduction of organic management from 5.3 to 3.5 t DM/ha/year (in pasture for harvesting only), and the number of cattle slightly decreased from 263 to 256 head. Therefore, organic beef production at Yakumo Farm may utilize more land per unit of beef than non-organic production, consistent with the results of de Vries et al. (2015). In Japan, the area of abandoned cultivated land has been increasing annually. It had reached 4230 km^2 by 2015, while the area of land still under cultivation was 44700 km^2. The Japanese national and local governments have been promoting the reuse of abandoned lands through the use of such land for cattle grazing (see Tsutsumi et al., 2014, 2016, 2012). By reusing abandoned lands, it may be possible to expand organic beef production in Japan.

4.3. Comparison of our results with previous reports

Environmental impacts in contrasting beef production systems have been assessed, and it is well known that they vary largely among systems (de Vries et al., 2015). de Vries et al. (2015) found that environmental impacts of beef could vary depending on the type of diet, origin of calves and type of production; for example, systems using culled dairy calves had smaller environmental impacts per unit of beef produced than suckler-based systems.

We compared the results of LCAs for suckler- and roughage-based (following the definition of de Vries et al. (2015)) beef production systems including grass-fed and organic systems (Beauchemin et al., 2011; Capper, 2012; Cardoso et al., 2016; Edwards-Jones et al., 2009; Lupo et al., 2013; Mogensen et al., 2015; Nguyen et al., 2010; Nguyen et al., 2012; Ogino et al., 2016; Pelletier et al., 2010; Ruviaro et al., 2015; Stackhouse-Lawson et al., 2012; Tsutsumi et al., 2017) with our results for Yakumo Farm (Table 9). For the cases that used live weight as the functional unit, we converted the live weight to carcass weight assuming the dressing percentage as 56%. Among the listed cases, GWP in the organic system was at the intermediate level, but that in the non-organic system was slightly greater. Similar results were found by comparing Yakumo Farm and the listed grass-fed systems. The AP and EP values in both the organic and non-organic systems were the lowest to third lowest of the listed cases, although only a small number of studies assessed both AP and EP. This was partly because of differences in methodological choices among the studies, such as the emission factors used for NH_3 from excreta and its management. For example, Nguyen et al. (2012) assumed that 12% of excreted N in barns was directly emitted as NH_3, and 6 % of the remaining N was also emitted as NH_3 through manure management, whereas we assumed values of 6.39 and 2.38%, respectively (Table 4). Energy consumption in the organic system was smaller than that of the listed cases, and was the greatest in the non-organic system. Accordingly, based on the comparisons above, the introduction of organic management at Yakumo Farm mitigated the GWP and energy consumption, leading to their positions in the intermediate and smaller ranges, respectively. The GWP and energy consumption largely varied among the listed cases for non-organic grass-fed beef production. Pelletier et al. (2010) estimated GWP and energy consumption in grass-fed beef production ("pasture" in Table 9) at 34.3 kg CO_2 equivalent (CO_2e) and 86.4 MJ per carcass weight (kg) respectively, which were similar to the values in the non-organic system in our analysis. However, Capper (2012) estimated them at 26.8 kg CO_2e and 12.3 MJ, respectively. These differences might stem from the intensity of fertilization in grass production. In the grass production system assumed by Pelletier et al. (2010), 112 to 168 kg of N fertilizer per hectare was applied annually, whereas less than 1 kg was applied in Capper (2012). Under non-organic management at Yakumo Farm, 55 kg of N fertilizer per hectare per year was applied to pastures for harvesting. These results suggest that grass-fed beef production with intensive chemical fertilizer application can increase GWP and energy consumption.

5. Conclusions

We performed a comparative LCA for grass-fed beef production at Yakumo Farm before and after the introduction of organic management, and the conventional Japanese system, which depends on imported concentrate feed. Both the organic and non-organic systems had much smaller AP, EP and energy consumption than the conventional system. Generally, the exclusion of feed transportation resulted in a reduction of these environmental impacts. The organic system had an equivalent GWP, but the non-organic system had a greater GWP than the conventional system. The use of chemical fertilizer increased the GWP in the non-organic system. The comparison of environmental impacts for Yakumo Farm and other previously reported beef production systems based on calves from suckler cows that are predominantly fed roughage indicated that: (1) the non-organic system had a slightly greater GWP and the greatest energy consumption; and (2) the organic system had an intermediate GWP and smaller energy consumption. Therefore, we conclude that introducing organic management at Yakumo Farm mitigated its environmental impacts. Our results provide implications for mitigating the environmental impacts caused by beef or other livestock production not only in Japan, but also in other countries depending upon imported feed.

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Table 1

Description of the three beef production systems

	Yakumo Farm		Conventional
	Organic	Non-organic	
All cattle			
Grazing period per year (days)	168	168	0
Cow-calf			
Age at first calving (days)	779	779	757
Calving interval (days)	395	395	417
Calving occurrences per cow	7	9	9
Lactation period (months)	6	6	3
Steer			
Daily weight gain (kg)	0.63	0.65	0.95
Age at slaughter (days)	1089	885	761
Live weight at slaughter (kg)	724	615	722
Cold carcass weight (kg)	410	339	465

Table 2
Feed composition for producing one marketed steer including cow-calf, backgrounding and finishing stages in the three beef production systems

	Yakumo Farm		Conventional
	Organic	Non-organic	
Feed produced in Yakumo Farm (kg dry matter)			
Grass (harvesting)	8157 [a]	6719 [b]	
Grass (grazing)	6785	5931	
Other farm-grown feed (kg)			
Italian ryegrass hay			2266
Rice straw			1437
Wild grass hay			515
Imported feed (kg)			
Maize			3098
Wheat bran			1330
Alfalfa hay			956
Soybean meal			833
Timothy hay			569

[a] Only silage.
[b] Silage and hay.

Table 3
Environmental loads associated with direct emissions of ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4) from soil in feed production, emission factors and referenced literature

	Unit	Emission factor	Reference
In Japan			
Rice paddy			
NH_3	% NH_3-N	8.1	Hayashi et al. (2008)
N_2O	% N_2O-N	0.31	GIO (2016)
CH_4	kg CH_4/ha/year	439	GIO (2016)
Other arable systems			
NH_3 (chemical fertilizer)	% NH_3-N	0.08	Hayashi et al. (2011)
NH_3 (manure)	% NH_3-N	0.8	Hayashi et al. (2009)
N_2O (chemical fertilizer)	% N_2O-N	1.39	Shimizu et al. (2013)
N_2O (manure)	% N_2O-N	0.46	Shimizu et al. (2013)
In the USA			
NH_3	% NH_3-N	7	Bouwman et al. (2002)
N_2O	% N_2O-N	1	IPCC (2006)

[1] The units, % NH_3-N and % N_2O-N, indicate the proportion of N emitted as NH_3 and N_2O, respectively, relative to the applied amount of N.

Table 4

Environmental loads associated with enteric emission, excreta and composting for ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4), emission factors or estimation equations, and referenced literature

Source	Unit	Emission factor or estimation equation	Reference
Enteric emission			
CH_4 (<5 months of age)	g/day	$-1.2 + 3.4 \times W$	Sekine et al. (1986)
CH_4 (others)	L/day	$-17.766 + 42.793 \times DMI - 0.849 \times DMI^2$	Shibata et al. (1993)
Excreta			
CH_4 (on pasture)	kg	VS × 0.095%	GIO (2016)
CH_4 (in barn)	kg	VS × 0.13%	GIO (2016)
NH_3 (on pasture)	% NH_3-N	3.8	Bouwman et al. (2002)
NH_3 (in barn)	% NH_3-N	6.39	Groot Koerkamp et al. (1998)
N_2O (on pasture)	% N_2O-N	0.684	GIO (2016)
Composting			
NH_3	% NH_3-N	2.38	Shiraishi et al. (2004)
N_2O	% N_2O-N	1.6	GIO (2016)

[1] W: age in weeks.
[2] DMI: dry matter intake per day (kg).
[3] VS: volatile solid (kg), estimated according to IPCC (2006).
[4] Amount of excreted nitrogen was estimated according to Terada et al. (1998).
[5] The units, % NH_3-N and % N_2O-N, indicate the proportion of N emitted as NH_3 and N_2O, respectively, compared with the N contained in excreta.

Table 5
Global warming potential of the three beef production systems, and the contribution of each process and substance (kg carbon dioxide equivalent per kg of cold carcass steer weight)

	Yakumo Farm		Conventional
	Organic	Non-organic	
Total	29.3	35.1	28.9
Process			
Roughage production (farm-grown)	2.8	8.4	1.9
Roughage production (USA)			0.3
Concentrate production (USA)			3.8
Feed transportation			7.0
Animal management	0.3	0.3	0.4
Enteric fermentation	21.7	22.1	12.3
Excreta and composting	4.5	4.4	3.2
Substance			
Methane (CH_4)	22.2	22.7	13.3
Carbon dioxide (CO_2)	2.0	5.6	11.2
Nitrous oxide (N_2O)	5.1	6.8	4.3

Table 6

Acidification potential of the three beef production systems, and the contribution of each process and substance (g sulfur dioxide equivalent per kg of cold carcass steer weight)

	Yakumo Farm		Conventional
	Organic	Non-organic	
Total	115.9	103.5	325.7
Process			
Roughage production (farm-grown)	10.0	13.1	1.6
Roughage production (USA)			4.3
Concentrate production (USA)			24.4
Feed transportation			218.2
Animal management	0.1	0.1	0.2
Excreta and composting	105.9	90.3	77.0
Substance [a]			
Ammonia (NH_3)	115.1	99.9	103.6
Nitrogen oxide (NO_x)	0.6	1.7	104.0
Sulfur dioxide (SO_2)	0.2	1.6	2.0
Sulfur oxide (SO_x)	0.1	0.4	116.1

[a] The values contributed by nitrogen dioxide (NO_2) were lower than 0.01 in all systems.

Table 7
Eutrophication potential of the three beef production systems, and the contribution of each process and substance (g phosphate equivalent per kg of cold carcass steer weight)

	Yakumo Farm		Conventional
	Organic	Non-organic	
Total	20.31	17.84	37.50
Process			
Roughage production (farm-grown)	1.71	1.97	0.23
Roughage production (USA)			0.74
Concentrate production (USA)			4.06
Feed transportation			18.94
Animal management	0.02	0.02	0.02
Excreta and composting	18.58	15.85	13.52
Substance [a]			
Ammonia (NH_3)	20.20	17.53	18.19
Nitrogen oxide (NO_x)	0.10	0.31	19.31

[a] The values contributed by NO_2 were lower than 0.01 in all systems.

Table 8
Energy consumption of the three beef production systems and the contribution of each process (MJ per kg of cold carcass steer weight)

	Yakumo Farm		Conventional
	Organic	Non-organic	
Total	29.1	117.9	190.1
Process			
Roughage production (farm-grown)	24.3	113.3	18.2
Roughage production (USA)			6.5
Concentrate production (USA)			62.8
Feed transportation			97.1
Animal management	4.8	4.6	5.6

Table 9

Comparison of environmental impacts of suckler- and roughage-based beef production systems (per kg of cold carcass weight)

Reference	Country	Description	Grass-fed	Organic	GWP ($kg\ CO_2e$)	AP ($g\ SO_2e$)	EP ($g\ PO_4e$)	Energy (MJ)
This study	Japan	Organic	Yes	Yes	29.3	115.9	20.3	29.1
	Japan	Non-organic	Yes	No	35.1	103.5	17.8	117.9
Edwards-Jones et al. (2009) [a]	UK	Conventional	No	No	27.7			
	UK	Extensive	No	No	85.0			
Pelletier et al. (2010) [a]	USA	Pasture	Yes	No	34.3		253.6	86.4
	USA	Backgrounding/Feedlot	No	No	28.9		212.5	80.4
Nguyen et al. (2010)	EU	Suckler cow-calf	No	No	27.3	210.0		59.2
Beauchemin et al. (2011)	Canada	Increased use of forages	No	No	23.1			
Capper (2012)	USA	Grass-fed	Yes	No	26.8			12.3
Nguyen et al. (2012)	France	Standard	No	No	27.8	169.0	98.0	64.8
	France	With omega-3 and linseeds	No	No	27.7	173.0	98.0	68.4
Stackhouse-Lawson et al. (2012)	USA	With stocker phase	No	No	22.6			
Lupo et al. (2013)	USA	Grassfed	Yes	No	31.5	299.1	35.1	
Ruviaro et al. (2015) [a]	Brazil	Natural grass	Yes	Yes	76.1			
	Brazil	Improved	Yes	No	41.6			
	Brazil	Supplemented	No	No	50.6			
Mogensen et al. (2015)	Denmark	Beef breed intensive, DK	No	No	23.1			
	Denmark	Beef breed extensive, DK	No	No	29.7			
	Sweden	Beef breed intensive, SE	No	No	25.4			
Cardoso et al. (2016)	Brazil	Pasture forage	Yes	Yes	49.6			
	Brazil	With protein and/or energetic supplements	No	No	31.0			
Ogino et al. (2016) [a]	Thailand	Extensive	Yes	No	25.0	83.9	53.6	6.3
Tsutsumi et al. (2017)	Japan	Grazing	No	No	27.8	153.2	20.3	134.2

[a] Because live weight was used as functional unit in these studies, we converted the live weight to carcass weight assuming the dressing percentage as 56%.

[1] GWP: global warming potential; AP: acidification potential; EP: eutrophication potential; CO_2e: carbon dioxide equivalent; SO_2e: sulfur dioxide equivalent; PO_4e: phosphate equivalent.