Economic and environmental impacts of changes in culling parity of cows and diet composition in Japanese beef cow-calf production systems

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Abstract

The effects of changes in culling parity of cows and diet composition on economic and environmental outputs in Japanese beef cow-calf production systems were deterministically analyzed using a herd model simulation. The model simulated the annualized net revenue as an economic indicator and the overall environmental index derived from a life cycle assessment (LCA) as an environmental indicator. Biological factors (survivability, growth, reproduction, and feed requirements) and economic factors (returns from sales of live calves and cows' carcasses and production costs) were included in the model. The model also included modified feed formulation methods, allowing us to analyze the effect of reductions in environmental loads caused by the change in diet compositions. The results of the present study indicated that later culling was economically and environmentally optimal under the current production system, which suggested that the selection of economically optimal culling parity of cows could result in environmentally optimization of the beef cow-calf production system. The difference in feed composition derived from the difference in feed formulation methods did not affect the determination of optimal culling parity, whereas the use of modified feed formulation methods could reduce environmental loads at a higher rate than that of economic benefits. However, the reduction rate of the environmental impact was much higher in the case of selection of the optimal culling parity than in the case of use of modified feed formulation methods, which stressed the importance of choosing the optimal culling parity of cows both from the economic and environmental points of view.

Key words: beef cow-calf production, optimal culling parity, annualized net revenue, environmental impact, life cycle assessment, modified feed formulation method

1. Introduction

As a result of the Kyoto Protocol, the environmental impacts of animal production have received increasing attention, and the focus of many studies in animal science has been to seek strategies to reduce environmental loads from domestic animals. Since consciousness of environmental problems such as global warming and water pollution has been increasing, animal producers have recognized the need to start efforts to decrease these environmental impacts (Ogino et al. 2004). However, the detrimental environmental impacts are costs that are typically unmeasured and often do not influence farmer choices about production methods (Tilman et al. 2002). In fact, reducing environmental loads from a cattle farm makes sense only if the farm is economically viable. Hence, sustainable animal production requires farm management that is both economically viable and environmentally sound (Thomassen et al. 2009), and thus economic performance and environmental performance should be inseparably assessed (Veysset et al. 2010).

Several mitigation strategies for reducing environmental loads have been proposed, and one of the strategies is alteration of diet composition (Beauchemin et al. 2011). To reduce environmental loads from animal excretion by changing feed composition, the use of modified feed formulation methods that can reduce both feed costs and environmental loads has been recommended (Tozer and Stokes 2001; Jean dit Bailleul et al. 2001; Oishi et al. 2011a). However, before implementing such feed formulation methods, the impact on total environmental loads arising from the entire production cycle should be assessed (Beauchemin et al. 2011), including the impact on the economics of the production system.

The life cycle assessment (LCA) method, which accounts for all changes in environmental emissions arising from a prospective mitigation practice in the entire farming system, is a useful tool to adequately assess these mitigation strategies (Beauchemin et al. 2010). LCA has become an internationally accepted method for assessing potential environmental impact of a product (Guinée et al. 2002), and many studies have used LCA to assess the environmental impact for specialized beef production systems in various regions (e.g., Ogino et al. 2004, 2007; Casey and Holden 2006; Beauchemin et al. 2010; Peters et al. 2010).

Improvements in the efficiency of a production system can have favorable effects on the reduction of overall emissions from the system (Wall et al. 2010). In cow-calf production systems, the parity of cows can affect some key elements related to the efficiency of production, such as the conception rate of cows and the weaning weight of their calves, indicating that the effect of the parity of cows in culling strategy can be an important factor when economic optimization of the production systems is targeted at a herd level. In recent years, Oishi et al. (2011b) have developed a model to determine an economically optimal culling parity of cows in beef cow-calf production systems and evaluated the effect of culling strategy of cows on the economics of the production systems. Nevertheless, the effects of culling strategy of cows on environmental loads at a herd level have received little attention for a beef cow-calf production system, although some studies reported the effect of dairy cows' longevity on the reduction of greenhouse gas emissions (e.g., Weiske et al. 2006; Bell et al. 2011).

The objective of the present study was to evaluate the effects of changes in culling parity of cows and diet composition on economic and environmental outputs in Japanese Black cow-calf production systems. The annualized net revenue was used as an economic indicator of the production, and the overall environmental index estimated from results of LCA was used as an environmental indicator of the production. Compared to an ordinal least-cost feed formulation method, two modified feed formulations methods that can reduce environmental loads were evaluated as methods for altering diet composition.

2. Materials and methods

2.1. General

Fig. 1 shows the outline structure of the model used in this study. The economic and environmental outputs of Japanese Black cow-calf production systems were simulated at the herd level. The model used in this study was based on the model described by Oishi et al. (2011b) and Oishi and Hirooka (2012). The annualized net revenue was adopted as an economic indicator, and an aggregated environmental impact (the overall environmental index) estimated by weighting of the normalized environmental impacts derived from LCA was used as an environmental indicator. All simulations were conducted deterministically based on a one-day time step, and subroutine DLPRS (revised simplex method) for linear programming implemented in the IMSL Math/Library (Visual Numerics, Inc. 1994) was used for linear programming in feed formulations.

2.2. Cow-calf model and input parameters

The default values of the biological and economic parameters in the cow-calf model are presented in Table 1. Birth and mature weights of females were set as fixed parameters. The weaning weight of calves was assumed to be expressed as a quadratic function of the parity of their dams using the data of Renquist et al.

(2006). The birth, weaning, and mature body weights of steers were expressed as 1.2, 1.08, and 1.2 times those of heifers, respectively. Body weight changes in each sex were estimated from the growth curves, which were represented by straight lines from birth to weaning and by Brody's curve (Brody 1945) from weaning. For pregnant cows, the total weight of the conceptus was added to the maternal weight in the last 2 months of pregnancy (AFRC 1993). Daily milk yields of cows were estimated using Wood's lactation curve (Wood 1967) based on the previous studies for Japanese beef cows (Hirooka et al. 1998; Gradiz et al. 2007). Details for the estimation of body weight changes and milk yields are shown in Appendix A.1 of the supplementary online materials.

The daily amounts of feeds fed to animals, which could satisfy nutrient requirements estimated based on the Japanese Feeding Standard for Beef Cattle (NARO 2009) with slight modifications according to AFRC (1993) and NRC (2000, 2001) (see Appendix A.2 of the supplementary online materials), were calculated using a feed formulation method described below. All cows and calves were assumed to be fed purchased feed in a barn and not grazed, because the Japanese Black cow-calf operation is typically relatively small-scale under a confinement management system and cows are managed individually with given roughage and restricted access to concentrate (Oyama et al. 2004). Ingredients of concentrate and roughage assumed were: corn, soybean meal, wheat bran, alfalfa hay cube, hay, and rice straw for growing steers and heifers, and corn, wheat bran, hay, and rice straw for cows, respectively, which were selected as the standard feeds in the Japanese cow-calf system (Ogino et al. 2007). The chemical composition of feeds (Table 2) was based on the Standard Tables of Feed Composition in Japan (NARO 2010). The use of supplemented feeds of pre-weaning calves was assumed when the net energy intake from the dam's milk was not sufficient for the net energy requirements of calves. Requirements for the following nutrients on an as-fed basis were set as the constraints of the feed formulation: dry matter (DM; kg/day), crude protein (CP; kg/day), total digestible nutrients (TDN; kg/day), neutral detergent fiber (NDF; kg/day), acid detergent fiber (ADF; kg/day), calcium (Ca; kg/day), and phosphorus (P; kg/day). The lower bounds of the feeding amounts for NDF and ADF were set to be 160 and 100 (g/kg, DM basis), respectively. The upper bound for the ratio of the feeding amount of wheat bran to concentrates was set to 25 (kg/kg) on an as-fed basis.

With respect to the survivability of animals, two cases of mortality were considered in the present study: pre-weaning calf mortality and annual cow mortality. The conception rates of cows by parity were calculated from a quadratic function of the number of parity estimated from Rogers (1972). Mating trial times were fixed for each reproduction cycle (Hirooka et al. 1998), and the average period from parturition to the next conception was estimated based on the method by Bailie (1982). The calving rate of cows was determined by calf losses considering the effects of abortions and of fetal and perinatal death. The replaced heifers that failed to conceive after the given mating trials were assumed to be culled immediately, and those that failed to deliver were culled at calving. If breeding cows failed to conceive and deliver, they were assumed to be culled when their calves were weaned. Details on the calculation of the mortality and reproductive traits are shown in Appendix B.1 of the supplementary online materials.

The carcass price of culled cows was predicted in each parity of cows at culling by the following quadratic equation under the assumption that the beef of all culled cows had a Japanese beef marbling standard (BMS) number of 3 (Table 1):

$$CP(pa) = 1.7145 pa^2 - 42.475 pa + 1118.6,$$

where $CP(pa)$ is the carcass price of cows (¥/kg carcass) and pa is the parity of cows at culling (Oishi et al. 2011b). The default values for the live female calf price per body weight (yen/kg) and the relative calf price ratio of live male to live female were derived from MAFF (2011). The prices of feeds were mostly identical to those reported by Oishi et al. (2011a), whereas the price of hay was modified and that of alfalfa hay cube was added based on MAFF (2010) (Table 2). Most beef cows are artificially inseminated (AI) in Japan and the technical costs for mating (AI semen cost and other veterinary costs per estrous cycle) were incorporated in the model. The other costs per day per calf including managerial costs and machinery costs were based on MAFF (2009).

The herd composition dynamics of the model included three animal categories: male calves, non-replacement female calves, and replacement heifers and cows. Self-replacement production was assumed throughout this study, and therefore it was necessary to control the replacement rate of cows to maintain the herd size with the changes in the planned culling parity of cows. Individual biological and economic production traits were multiplied by the animal numbers of the herd components, which were derived from the replacement rate. Details for the herd composition dynamics are presented in Appendix B.2 of the supplementary online materials.

2.3. Feed formulation methods at an individual level

Feed rations at an individual level were determined for a cow and her calves using a feed formulation method based on linear programming in the present study. The ordinal least-cost feed formulation (Method 1) was used in the base simulation, and two alternative feed formulation methods were examined for their potential to reduce environmental loads: the least-excretion feed formulation (Method 2) to reduce both feed cost and nitrogen and phosphorus excretions (Oishi et al. 2011a), and the novel least-emission feed formulation (Method 3), which can reduce both feed cost and environmental emission gases at the feed production and transport stages.

The ordinal least-cost feed formulation (Method 1) and the least-excretion feed formulation (Method 2) are expressed in the following formulas:

$$\min C = \sum_{i=1}^{n} c_i x_i \qquad \text{: Method 1}$$

$$\min C = \sum_{i=1}^{n} (c_i + \beta_N N_i + \beta_P P_i) x_i \qquad \text{: Method 2}$$

$$\boldsymbol{AX} \geqq, =, \text{or} \leqq \boldsymbol{B}$$

$$\boldsymbol{X} \geqq \boldsymbol{0},$$

where n is the number of feed ingredients, c_i is the cost of the ith ingredient, x_i is the amount of the ith ingredient in the vector $\boldsymbol{X}$, β_N and β_P are the weight coefficients representing the assumed costs associated with nitrogen and phosphorus contents, N_i and P_i are the amounts of nitrogen (crude protein content divided by 6.25) and phosphorus in the ith ingredient, C of Method 1 is the ingredient mix cost, and C of Method 2 is the ingredient mix cost including the environmental cost per unit weight. In addition, $\boldsymbol{A}$ is the coefficient matrix of the system, where each a_{ij} represents the amount of nutrient value j in the ith ingredient and $\boldsymbol{B}$ is the vector of nutrient constraints based on the requirements of the animals. The weight constants β_N and β_P in the objective function of Method 2 are used as the penalty costs for nitrogen and phosphorus excretions, and they were assumed to be 2.30 and 3.92 (euro/kg) (276.0 and 470.4 (yen/kg) assuming 120 yen = 1 euro), respectively, based on the levy for nitrogen and phosphorus excretions by the Mineral Accounting System (MINAS) in the Netherlands (Hanegraaf and den Boer 2003) since such levies are still not introduced in Japan. The penalty costs were used only for reducing excretions and were not included in total feed cost; hence, the total feed cost was calculated as $\sum_{i=1}^{n} c_i x_i$.

The least-emission feed formulation method (Method 3) was newly developed for minimizing both feed cost and environmental impact emitted from feed production and feed transport stages. In this method, we revised the objective function in Method 2 as follows:

$$\min C = \sum_{i=1}^{n} (c_i + \sum_{j=1}^{z} \sum_{k=1}^{y} ((Ep_{k,j,i} + Et_{k,j,i}) \times CH_{k,j}) \times T_j) x_i \qquad \text{: Method 3,}$$

where $Ep_{k,j,i}$ is the emissions of a substance k for the potential impact category j when the ith ingredient is produced, $Et_{k,j,i}$ is the emissions of a substance k for the potential impact category j when the ith ingredient is transported, $CH_{k,j}$ is the characterization factor for a substance k in the potential impact category j, y is the number of substances in each potential impact category, T_j is the weighting factor for the potential impact category j, z is the number of potential impact categories, n is the number of feed ingredients, and x_i is the amount of the ith ingredient in the vector $\boldsymbol{X}$ shown in Methods 1 and 2. The coefficient matrix $\boldsymbol{A}$, the vector $\boldsymbol{B}$, and their relation are the same as in Methods 1 and 2. In the present study, the substances included carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ammonia (NH3), nitrogen oxide (NO_x), and sulphur dioxide (SO_2). The characterization factors were introduced to evaluate the potential impact for each category (e.g., the CO_2-equivalent amount for global warming potential), and the weighting factors were used as the penalty coefficient for each potential impact category in a similar fashion as in Method 2. Details of the calculation of emissions, the characterization factors, and the determination of potential impact categories by LCA will be described in the next section. The weighting factor for this method was derived from Ecotax weighting factors developed by Finnveden et al. (2006). The total feed cost was calculated in the same manner as in Methods 1 and 2, i.e., as $\sum_{i=1}^{n} c_i x_i$.

2.4. Life cycle assessment (LCA)

Environmental impacts in this study were calculated following the LCA study by Ogino et al. (2007).

The first step of LCA is to define the goal and scope of the analysis, the functional unit, and the system boundaries. In this study, the goal of LCA was to evaluate environmental impacts of Japanese beef cow-calf production systems at the herd level and to analyze the effects of changes in optimal culling parity and diet composition on the environmental impacts of production systems. The functional unit was defined as 1 kg of total weight output of live calves and culled cows from birth to culling. This study performed a “cradle-to-farm gate” LCA, and the activities in the herd level’s beef cow-calf life cycle system taken into account were feed production, feed transport, animal management, biological activity of animals, and waste treatment (Fig. 1). The environmental loads associated with transporting calves and cows to markets and the production of capital goods were excluded from the assessment. Excretion from cattle in Japan was assumed to be treated only by composting without forced aeration, in accordance with Haga (1999). The finished compost was regarded as organic fertilizer and not included in the system.

The phase of life cycle inventory analysis is to draw up an inventory of all the resources used and all the emissions released into the environment connected with all processes in the system. All environmental loads associated with the beef cow-calf production system, output coefficients, and condition settings for feed production and transport, animal management, biological activity of animals, and waste treatment were set to be similar to those used by Ogino et al. (2007), whereas diet composition was altered daily using a feed formulation method, and therefore emissions from feed production and transport were estimated per 1 kg of each feed ingredient on as-fed basis in this study (Table 3). Although enteric CH_4 emission by cattle can be generally estimated from gross energy intake using a formula recommended by IPCC (2006), enteric CH_4 emission for post-weaning animals (steers, heifers, and cows) was calculated from dry matter intake using the quadratic equation by Shibata et al. (1993) and Shibata and Terada (2010), which has been adopted for the emission estimation method in the National GHG Inventory Report of Japan (Ministry of the Environment, Japan 2011). For pre-weaning calves, the CH_4 emission was calculated as a function of week of age using the equation reported by Sekine et al. (1986). The amounts of nitrogen and phosphorus excretions were calculated as the differences between nitrogen intake and retained nitrogen and between phosphorus intake and retained phosphorus, respectively (NARO 2009). From the inventory, emissions of CO_2, CH_4, N_2O, NH_3, NO_x, and SO_2 were calculated for each activity. Emissions of CO_2 from cattle respiration and the composting of cattle waste were assumed to be offset by carbon fixation through photosynthesis from the atmosphere into forage crops in accordance with Ogino et al. (2007). Soil organic carbon sequestration was also excluded because of no grazing pastures in the present study, although Pelletier et al. (2010) reported the possibility of substantial reductions in net CO_2 emissions from pasture systems under conditions of positive carbon sequestration potential.

The contribution of the beef cow-calf production system to global warming, acidification, and eutrophication was examined in this study. The global warming potential (GWP) was computed according to the CO_2-equivalent characterization factors for CO_2: 1, CH_4: 25, and N_2O: 298, which were based on a time horizon of 100 years (IPCC 2007). The SO_2-equivalent characterization factors for SO_2: 1, NO_x: 0.7, and NH_3: 1.88 and the PO_4-equivalent characterization factors for NO_x: 0.13 and NH_3: 0.33 derived from Heijungs et al. (1992) were used to evaluate the acidification potential (AP) and eutrophication potential (EP), respectively.

2.5. Evaluation of the production system

The effects of the culling parity of cows on the annualized net revenue and the overall environmental index were examined in the beef cow-calf production system in this study. The planned culling parity showing the highest annualized net revenue and/or the overall environmental index can be regarded as the optimal targeted herd life.

The annualized net revenue is calculated based on Meadows et al. (2005) as follows:

$$NPV(pa) = \sum_{i=0}^{Day(pa)} \left(CF(i) \big/ (1+dr)^i \right)$$

$$EDC(pa) = NPV(pa) \times dr \big/ \left(1 - \left(1 \big/ (1+dr)^{Day(pa)}\right)\right)$$

$$AN(pa) = EDC(pa) \times 365,$$

where $NPV(pa)$ is the net present value of the herd associated with keeping cows until planning culling parity pa, $Day(pa)$ is the number of planning days until parity pa, $CF(i)$ is the total daily cash flow of the herd reflecting the herd composition dynamics, dr is the daily discount rate, $EDC(pa)$ is the equivalent daily cash flow of the herd associated with keeping cows until planning culling parity pa, and $AN(pa)$ is the annualized net revenue (or the estimated equivalent annuity). The daily cash flow is defined as the daily return (estimated only in cases where calves or beef from culled cows are sold) minus the daily cost (including feed cost, AI cost, and other fixed cost) for cows of age i in days and their calves. The daily discount rate is calculated from the annual discount rate as $dr = \sqrt[365]{(1+ydr)} - 1$, where ydr is the annual discount rate. The annual discount rate in this study was assumed to be 5%.

On the other hand, the environmental impacts derived from LCA were normalized and aggregated to one environmental index that enabled us to evaluate the balance between the environmental output and the economic output (i.e., AN) of the production system. The normalization is performed in order to assess the relative contribution of the production to the environmental impacts (e.g., Van der Werf et al. 2005), and the normalized indicator values become dimensionless, which is a prerequisite for a final aggregation across all LCA impact categories to one overall environmental index (Brentrup et al. 2004). The aggregation to one environmental index is performed using a multi-criteria analysis tool and facilitates decision-making by producers. In the present study, the overall environmental index estimated by aggregating three impact categories was calculated using the method reported by Hermann et al. (2007) as follows:

$$OI = \sum_{j=1}^{z} \left(\sum_{k=1}^{y} (E_{k,j} \times CH_{k,j}) / N_j \right) \times V_j ,$$

where OI is the overall environmental index, $E_{k,j}$ is the emissions of a substance k for the potential impact category j, $CH_{k,j}$ is the characterization factors for a substance k in the potential impact category j, y is the number of substances in each potential impact category, N_j is a normalization factor for the potential impact category j, V_j is a valuation factor for the potential impact category j, and z is the number of potential impact categories (=3 in this study). The normalization factors were set to be 4.2×10^{13}, 3.2×10^{11}, and 1.4×10^{11} for GWP, AP, and EP, respectively, which were estimated values for world use (CML 2010). The valuation factors for GWP, AP, and EP were assumed to be 0.545, 0.286, and 0.169, respectively, using the analytical hierarchy process method as reported by Hermann et al. (2007), under the assumption that the order of importance of the impact categories for the global scale, highest to lowest, was GWP, AP, and EP.

3. Results

The annualized net revenue and the overall environmental index with the change in the planned culling parity of cows are presented in Fig. 2. Note that planned culling parities from the third to the twelfth were simulated because the herd cannot maintain the initial number of cows with only home-bred replacement heifers when reproduction occurs less than three times per cow. In addition, extremely small numbers of the overall environmental index were due to the large normalization factors for the global system used as a reference and the relative comparison of the index was required. The culling parity with the highest annualized net revenue was the 9th parity and that with the lowest overall environmental index was the 10th parity, and the annualized net revenue was increased and the overall environmental index was decreased with an increase in culling parity until the optimal culling parities. The results indicated that an increase in culling parity until the economically optimal parity could lead to reduction of the overall environmental index. In contrast, the difference in feed formulation methods did not change the optimal culling parity for either the annualized net revenue or the overall environmental index (result not shown).

Fig. 3 shows the reduction rates of the annualized net revenue and the overall environmental index when using the least-excretion feed formulation (Method 2) or the least-emission feed formulation (Method 3). By the use of either of these methods of feed formulation, the annualized net revenue and the overall environmental index were both reduced compared with the use of the ordinal least-cost feed formulation (Method 1). The reduction rate of the overall environmental index was much higher than that of the annualized net revenue, and the reduction rate of the overall environmental index by the use of Method 3 was slightly lower than that by the use of Method 2. When considering each impact category, all impact potentials for the three impact categories were lowest by the use of Method 2 and highest by the use of Method 1 (Table 4).

Fig. 4 shows the effect of change in the culling parity of cows on the annualized net revenue per yearly overall environmental index, which was used as an integrated annual economic and environmental index in this study. The unit for the environmental impact was set as the annual impact per production system, since the annualized net revenue indicates an annual economic output per production system. From the result of the analysis, economically and environmentally optimal culling parity could be assumed to be the 10^{th} parity, but the integrated economic and environmental index was not greatly reduced at more than the 10^{th} parity. The economic and environmental index under the optimal culling solution (at the 10^{th} parity) was almost twice as great as the index when cows were culled at the 3^{rd} parity.

4. Discussion

With an increase in culling parity until the 9^{th} parity, the economic benefit increased but the environmental impact decreased, indicating that selection of economically optimal culling parity could also make the beef cow-calf production system environmentally preferable. Moreover, as shown in Fig. 4, the integrated economic and environmental index was maximized when culling of cows occurred at a later parity. With respect to economic performance, previous studies showed that later culling was economically optimal (Oishi et al. 2011b; Oishi and Hirooka 2012), and the results were in agreement with other studies (Bourdon and Brinks 1987; Melton et al. 1994). With respect to environmental performance, Ogino et al. (2007) reported that an increase in the number of calves decreased the environmental impacts per calf, since environmental loads related to heifer rearing were shared by more calves. Beauchemin et al. (2011) also reported that increasing the longevity of cows in the herd led to reduction of environmental loads. Therefore, the result of the present study, which showed the positive effect of the longevity of cows on the reduction of environmental loads, was in accordance with the results of the two previous studies (Ogino et al. 2007; Beauchemin et al. 2011).

Comparison of the three feed formulation methods showed that the overall environmental index obtained from Method 2 was the lowest. This was an unexpected result, because the overall environmental index from Method 3 that minimizes emissions (i.e., environmental loads) was expected to be the lowest. Beauchemin et al. (2010) mentioned that implementing a mitigation strategy aimed at one part of a cattle production system could lead to an increase in environmental loads from other parts and therefore could not always guarantee a reduction in the total environmental load throughout the production cycle. Indeed, in this study, Method 3 could reduce the overall environmental index at a slightly higher rate than Method 2 at the feed production and transport stages, whereas Method 2 could reduce the index at a much higher rate than Method 3 at the animal and waste management stages (Fig. 5). This result suggested that the selection of feeds producing low emissions at the feed production and transport stages did not increase enteric CH_4 emission by animals due to small changes in dry matter intake but had a potential to increase environmental loads from animal excretion at the waste treatment stage. Therefore, if alteration of diet formulation is conducted for a mitigation of emissions, the impact of environmental loads from animal excretion on LCA evaluation for whole systems should be taken into account. In addition, one important issue that should be addressed here is that the magnitude of the penalty coefficients affects the result of feed formulation. A previous study (Oishi et al. 2011a) indicated that the effect of reducing nitrogen and phosphorus excretions was strengthened when the nitrogen and phosphorus penalty coefficients were set to be twice the default penalty coefficients. Therefore, when altering a feed formulation in order to reduce emissions, it should be important to consider whether the magnitude of penalty coefficients is adequate.

Meanwhile, the use of Method 2 or 3 could reduce only 1.5 to 1.6% of the overall environmental index compared with the use of the ordinal least-cost feed formulation (Method 1) (Fig. 3). In contrast, the reduction rate of the overall environmental index through the change in culling parity from the 3rd to the 10th parity was 11.9% (Fig. 2). However, the reduction rates of environmental loads based on the change in culling parity were comparatively low in the previous reports by Ogino et al. (2007) and Beauchemin et al. (2011), possibly because they examined only the effect of the extension of culling parity of cows from the 7th to the 8th or 9th parity on the reduction of environmental loads; that is, these studies did not consider the curvilinear effect of the change in culling parity of cows on environmental loads at a herd level. The results of the present study indicated that the curvilinear effect would lead to a higher reduction rate of the overall environmental index when the effect was countered through changes of culling parities assumed in simulation, which could stress the importance of choice of optimal culling parity from the environmental point of view.

There are broad uses of monetary-based weighting methods such as ExternE (European Commission 2005), EPS (Steen 1999) and Ecotax in environmental systems analysis tools (Ahlroth et al. 2011). In this study, however, the monetary-based weighting method for emissions (Ecotax) was only used as the penalty coefficients for emissions in the least-emission feed formulation method, and it was not used to integrate economic and environmental evaluations as a monetary basis in whole farm analysis. This was because a number of different approaches for weighting environmental impacts on a monetary basis may provide different economic values. Ahlroth and Finnveden (2011) compared four monetary-based weighting methods and reported that the results were similar in relative ranking of impacts although all of the methods gave different economic values. However, it might be difficult to consider other additional economic effects (e.g., discounting) on the environmental costs derived from the monetary weighting methods. For the reason, we adopted the overall environmental index estimated using a non-monetary weighting as an environmental indicator in this study.

The results from our study may be used for decision making by policy-makers. When the proposed system is different from the actual current system, policy-makers can design policy to address the reforms needed to move the systems to the proposed system. Our recommendation based on the present model is that later culling is economically and environmentally optimal in beef cow-calf production systems in Japan. In the actual Japanese cow-calf systems before 1990s, cows which calved 9 to 12 times in their lifetime were dominant (Oyama et al. 2007), which is consistent with our results. In recent years, some farmers may tend to cull cows at earlier parities, which might be a cause of high variability of calf market prices in short terms. It is however noticed that there is a diversity of cow-calf management systems in Japan, with smallholders in rural mountain areas usually keeping less than ten cows and retaining them as long as they produce calves. Such production systems are generally combined with cash crops (i.e., mixed farming systems) and are environmentally sound because of their enhanced nutrient cycles within the systems. Our recommendation may encourage such smallholders and also drive ordinary farmers to alter their culling strategies in order to achieve more economically and environmentally beneficial production systems.

Sustainable agricultural production can be defined as practices that meet current and future societal needs for food, ecosystem services, and healthy lives, by maximizing the net benefit to society when all costs and benefits of the practices are considered (Tilman et al. 2002). Thomassen et al. (2009) also stated that sustainability of agricultural production is a holistic concept consisting of three domains: economic, environmental, and social. In these three domains, ecologically sustainable production is that in which its polluting emissions and its use of natural resources can be supported by the natural environment in the long term (Thomassen et al. 2008), and economically sustainable production is that in which the farmers can continue their business with consistent economic profit gains. However, maximizing at least these two domains in parallel is generally difficult to achieve because of the frequent trade-offs among competing economic and environmental goals. In such a context, farmers can be expected to focus first and foremost on protecting their revenues rather than on protecting the environment (Veysset et al. 2010). For the two mitigation strategies analyzed in this study (i.e., changes in culling parity and feed composition), the results of the study showed that the use of modified feed formulation methods considering environmental loads (Methods 2 and 3) could result in environmentally positive but economically negative effects on the production system, whereas optimal culling decisions could generate economical and environmental benefits for the production system. Therefore, it is suggested that some mitigation strategies have the trade-off effect but others can achieve both economic and environmental goals. Consequently, the most important point is that we should search optimal solutions by combining several mitigation strategies that can maximize environmental benefits in keeping with satisfied economic needs of farmers.

5. Conclusions

This study evaluated the effects of changes in culling parity of cows and diet composition on economic and environmental outputs in Japanese beef cow-calf production systems. The model simulated the annualized net revenue (economic indicator) and the overall environmental index (environmental indicator) estimated from a life cycle assessment (LCA). Several feed formulation methods were also analyzed as a way to evaluate the effect of reduction of environmental loads caused by the changes in diet composition. The results indicated that later culling (the 10^{th} parity of culling) was economically and also environmentally valuable under the current production system. The difference in feed formulation methods did not affect the determination of optimal culling parity, but the use of modified feed formulation methods could reduce environmental loads much more than economic benefit. However, the reduction rate of the environmental impact was much higher by the selection of optimal culling parity than by the use of modified feed formulation methods. Therefore, it can be concluded that determination of optimal culling parity is essential for accomplishing economically and environmentally sustainable advances in beef cow-calf production systems.

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Appendices - Supplementary online materials

Supplementary materials associated with this article can be found in the online version.

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Table 1.
Base input parameters of the model in this study

Parameters	Units	Default values
Birth weight (x 1.2 for males)	*kg*	30 (females)
Mature weight (x 1.2 for males)	*kg*	515 (females)
Total annual milk yield	*kg*	970
Wood's curve parameter for lactation *b*		0.073
Wood's curve parameter for lactation *c*		0.0056
Protein content of milk of Japanese Black cows	*g/kg*	41
An estrus postpartum interval	*d*	40
Mean length of the estrous cycle	*d*	21
Mating trial times	*n*	5
Calving rate		0.98
Gestation length	*d*	285
Weaning age	*d*	150
Age at first mating	*d*	420
Pre-weaning calf mortality		0.02
Annual mortality rate after weaning		0.02
Dressing rate of culled cows		0.6135
Age at calf market	*d*	285
Metabolizability of feeds for pregnant and lactating cows		0.6
Metabolizability for dietary supplemented feed		0.534
Beef marbling score of culled cows	*n*	3
Live female calf price	*yen/kg*	1450
Relative calf price ratio of live male to live female		1.1344
Technical cost[1)]	*yen/mating*	12000
Other cost[2)]	*yen/d calf*	392

[1)] Includes AI cost and other veterinary and labor costs.

[2)] Includes managerial costs and machinery costs.

Table 2.
Composition of ingredients[1] and the ingredient prices[2] used in this study

	DM g/kg	CP g/kgDM	TDN g/kgDM	NDF g/kgDM	ADF g/kgDM	Ca g/kgDM	P g/kgDM	Price yen[3]/kg
Corn	855	89	936	125	36	0.3	3.0	40.1
Soybean meal	882	511	870	155	96	3.7	7.2	65.3
Wheat bran	868	181	723	427	141	1.2	11.4	32.7
Alfalfa hay cube	879	190	568	386	301	16.6	2.5	42.9
Hay[4]	851	114	617	645	394	4.7	2.8	41.6
Rice straw	878	54	429	631	392	3.0	1.4	36.0

[1] National Agriculture and Food Research Organization (2010): DM, CP, TDN, NDF, ADF, Ca, and P are total dry matter, crude protein, total digestible nutrients, neutral detergent fiber, acid detergent fiber, calcium, and phosphorus, respectively.

[2] The prices of feeds were mostly identical to those reported by Oishi et al. (2011a), whereas the price of hay was modified and that of alfalfa hay cube was added based on MAFF (2010).

[3] 1 euro = 120 yen

[4] Includes Italian ryegrass hay, timothy hay and orchardgrass hay, based on Ogino et al. (2004).

Table 3.
Amount of emissions[1)] for each feed ingredient (g/kg as-fed basis) at feed production and transport stages

Ingredient[2)]	CO_2 (g/kg)	SO_2 (g/kg)	NO_x (g/kg)	CH_4 (g/kg)	N_2O[3)] (g/kg)	NH_3[3)] (g/kg)
Corn	388.3141	0.1514	1.1978	0.0001	0.3144	2.0169
Soybean meal	522.8198	0.2088	2.0993	0.0008	0.1548	0.4196
Wheat bran	473.5041	0.1663	1.7211	0.0005	0.3188	1.6040
Alfalfa hay cube	209.2550	0.0904	0.4616	0.0000	0.0578	0.1261
Hay	241.5274	0.0916	0.8079	0.0000	0.1430	0.8928
Rice straw	135.2593	0.2111	0.3410	0.0814[4)]	0.0840	0.7587

1) Emissions relevant to energy use at feed production and transport stages were estimated from the inventories used by Ogino et al. (2007), although the domestic land transport distance was slightly modified.

2) Only rice straw was assumed to be domestically produced; others are imported.

3) NH_3 and a part of N_2O are emitted from soil (crop fields and paddy fields) at the feed production stage, as estimated by the amount of nitrogen input from chemical fertilizer applied. NH_3 from soil was estimated from the inventory used by Ogino et al. (2007), but N_2O from crop fields and paddy fields was estimated by the Ministry of the Environment, Japan (2011), respectively.

4) A large amount of CH_4 is emitted from flooded paddy fields, which was estimated by the Ministry of the Environment, Japan (2011).

Table 4.
Amount of emission for each impact category when the culling parity of cows was set to the environmentally optimal parity (the 10th parity)

Impact category[1)]	Feed formulation method[2)]		
(/kg weight of calves and culled cows)	Method 1	Method 2	Method 3
GWP (kgCO_2-eq.)	18.799	18.569	18.590
AP (kgSO_2-eq.)	0.1369	0.1307	0.1311
EP (kgPO_4-eq.)	0.0231	0.0226	0.0227

[1)] GWP: global warming potential, AP: acidification potential, EP: eutrophication potential
[2)] Method 1: ordinal least-cost feed formulation, Method 2: least-excretion feed formulation, Method 3: least-emission feed formulation

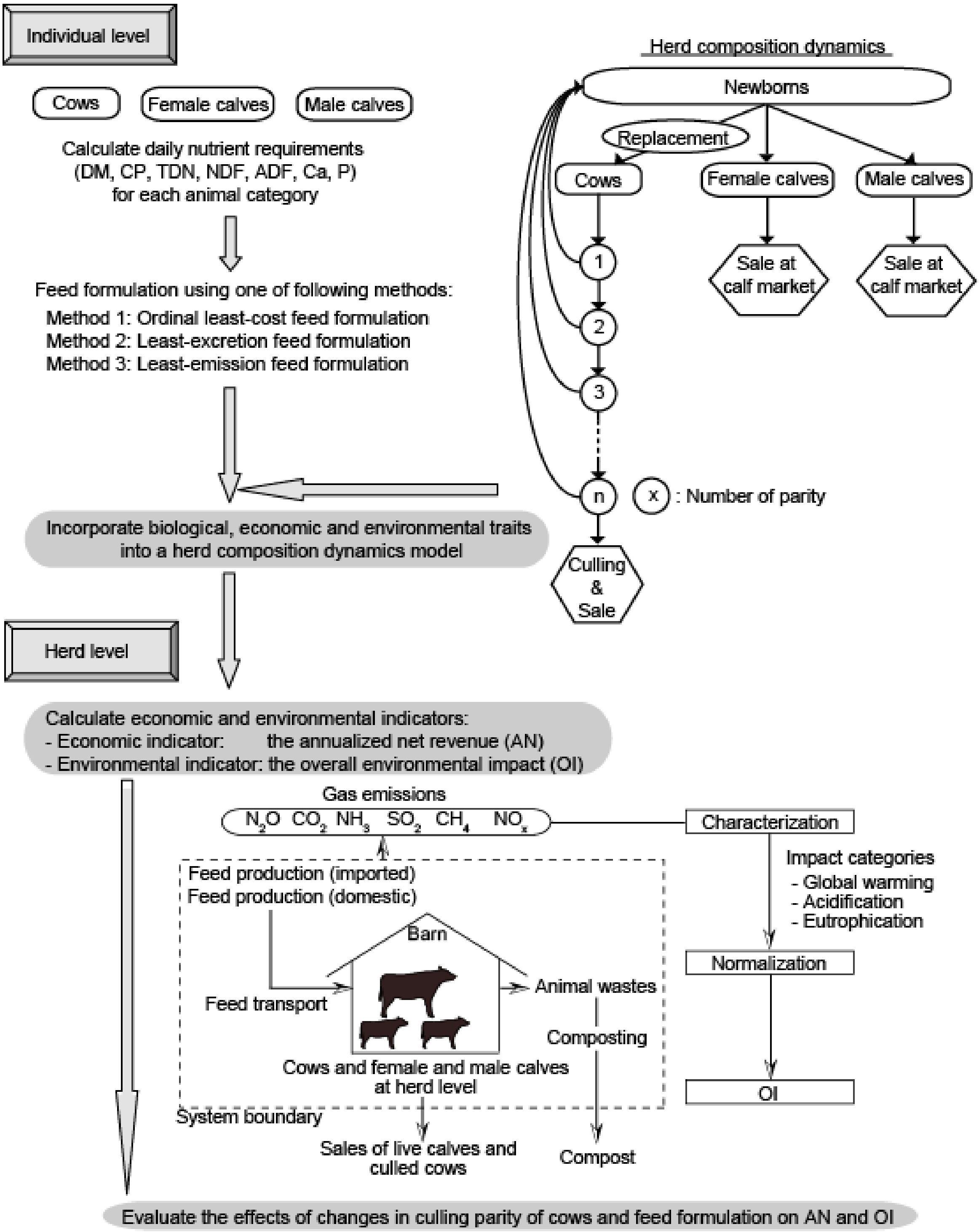

Fig. 1. Outline of the model structure.

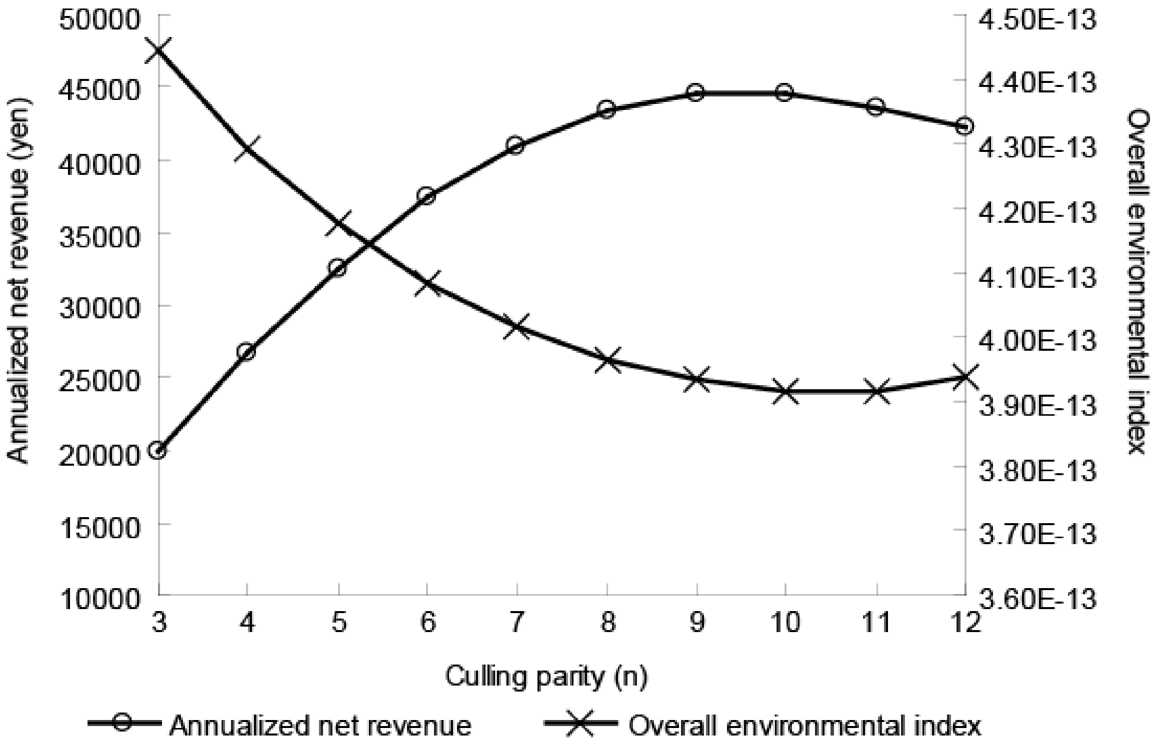

Fig. 2. Effects of the change in culling parity of cows on the annualized net revenue and the overall environmental index.

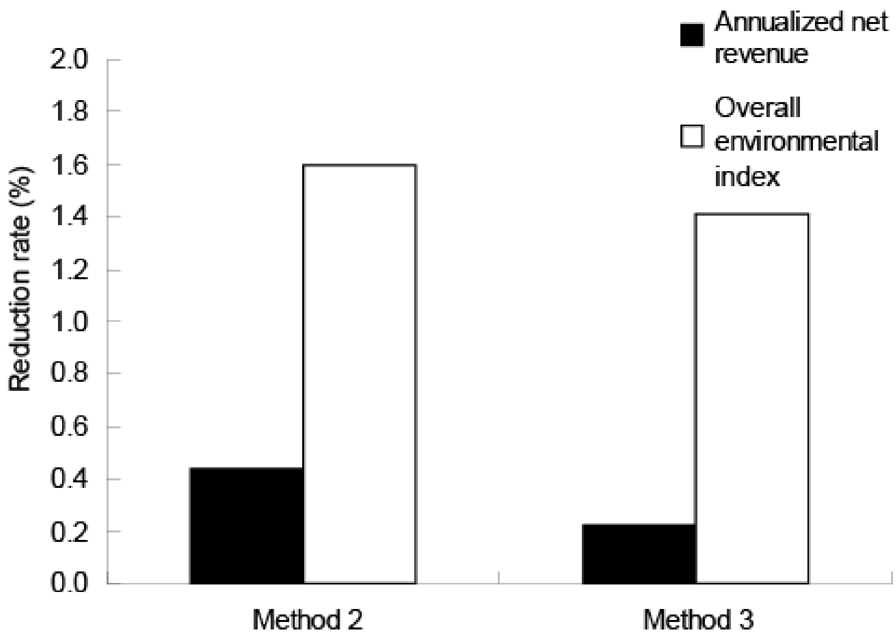

Fig. 3. Reduction rates of the annualized net revenue and the overall environmental index using the least-excretion feed formulation (Method 2) or the least-emission feed formulation method (Method 3) when the culling parity of cows was set to the environmentally optimal parity (the 10th parity). Reduction of the annualized net revenue indicates an economically negative effect, and that of the overall environmental index indicates an environmentally positive effect.

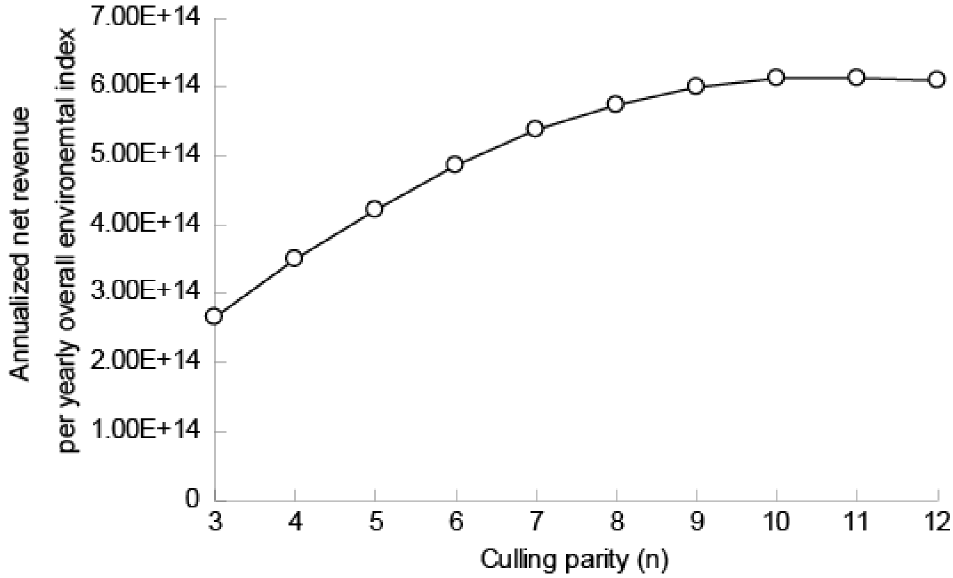

Fig. 4. Effect of the change in culling parity of cows on an integrated economic and environmental index (the annualized net revenue per yearly overall environmental index in this study).

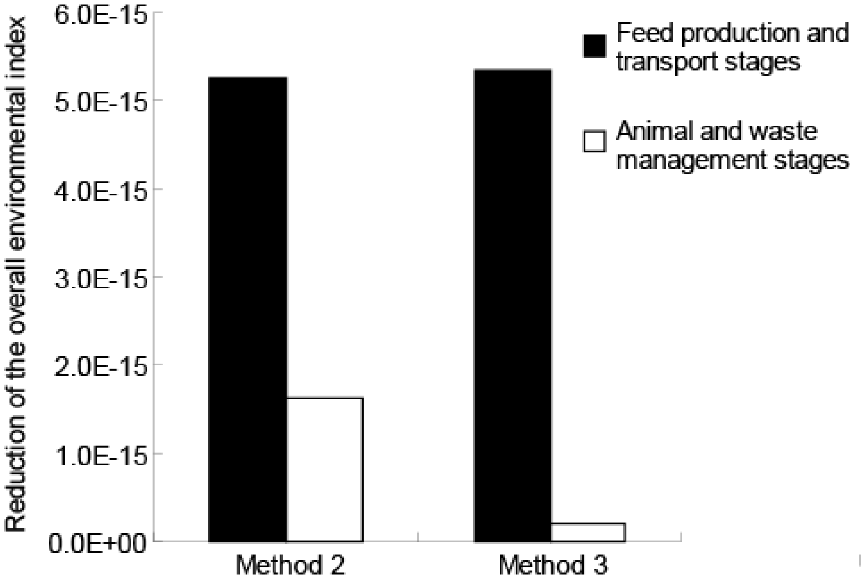

Fig. 5. Reduction of the overall environmental index for the feed production and transport stages and the animal and waste management stages using the least-excretion feed formulation method (Method 2) or the least-emission feed formulation method (Method 3), when the culling parity of cows was set to the environmentally optimal parity (the 10th parity). The reduction of the overall environmental index indicates an environmentally positive effect.

Economic and environmental impacts of changes in culling parity of cows and diet composition in Japanese beef cow-calf production systems

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Appendices – Supplementary online materials

Symbols

x (subscript)	sex: m = male, f = female
t	age in days

Appendix A - Calculation of weight changes, milk yields and nutrient requirements of animals

1. Weight changes and milk yields

Weaning weights of calves

The weaning age (t_{wean}, days) is assumed to be 150 days of age and is a fixed parameter in the present study. The weaning weight (WW_x, kg) of calves was assumed to vary according to the changes in parity of their dams, and is expressed as a quadratic function as:

$$WW_x = (-0.0091n^2 + 0.1081n + 0.7318) \times 180,$$

where n is the number of parities. The curving pattern of the change in weaning weight in the equation, expressed by the quadratic function in parentheses, was derived from the data of Renquist et al. (2006), and the function was multiplied by a fixed number in order to correct the expression to fit the situation in Japan.

Growth and milk yields

The form of the growth curve is expressed using birth weight (BW_x, kg) and WW_x as:

$$W_x(t) = (WW_x - BW_x)/t_{wean} \times t + BW_x \quad (t \leq t_{wean})$$

$$W_x(t) = A_x(1 - B_x e^{-K_x t}) \quad (t > t_{wean}),$$

where A_x, B_x and K_x are Brody's growth curve parameters. From these functions, the daily gain ($DG_x(t)$, kg/day) is expressed as:

$$DG_x(t) = (WW_x - BW_x)/t_{wean} \quad (t \leq t_{wean})$$

$$DG_x(t) = K_x(A_x - W_x(t)) \quad (t > t_{wean}).$$

Here, Brody's parameter A_x is assumed to be mature weight (MW_x, kg). Since both functions of $DG_x(t)$ should be equal at weaning, parameters B_x and K_x can be calculated as:

$$B_x = (1 - WW_x / MW_x)e^{K_x t_{wean}}$$

$K_x = ((WW_x - BW_x)/t_{wean})/(MW_x - WW_x)$.

The conceptus weight added to the maternal weight for the last 2 months of pregnancy ($W_c(t_c)$, kg) is estimated as (AFRC 1993):

$W_c(t_c) = (BW/40) \times 10^{(2.932 - 3.347\exp(-0.00406 t_c))}$,

where t_c (days) is days from conception ($222 \le t_c \le t_{preg}$).

Daily milk yields of cows (MY, kg/day) were estimated using Wood's lactation curve (Wood 1967) as:

$MY(t_m) = a t_m{}^b e^{-ct_m}$,

where t_m (days) is days after calving, and a, b and c are Wood's parameters. In the model, parameters b, c and total milk yield in the lactation period (TM, kg) are given as animal traits as shown in Table 1. Using these parameters, the parameter a is calculated as:

$$a = \left(\sum_{t_m}^{t_{wean}} t_m{}^b e^{-ct_m}\right) \Big/ TM .$$

2. Estimation of nutrient requirements

The nutrient requirements of Japanese beef cow-calf production at an individual level were estimated mainly based on NARO (2009) with slight modifications according to AFRC (1993) and NRC (2000, 2001). Briefly, the expressions used to calculate nutrient requirements are separated into two categories: pre-weaning calves and post-weaning animals (steers, heifers and cows). The estimation of nutrient intakes for pre-weaning calves accounts for the nutrients from the cow's milk and dietary feed (roughage and concentrates).

Estimation of DM and TDN intakes from dietary feed for pre-weaning calves

In this study, the energy requirements of calves were assumed to be supplied only by their cow's milk from birth to 30 days of age; from 30 days of age to the weaning age, the energy resources were assumed to be provided by both cow's milk and dietary feed supplementation. It was also assumed that the cow's milk was completely consumed and that deficiencies in meeting energy requirements were made up for by dietary supplemented feed. The DM and TDN intakes from dietary feed was estimated from the differences between the net energy requirements of all calves born from a cow and the net energy contained in the milk produced by the cow.

The expressions for converting ME values to the net energy required for maintenance (*NEm*, Mcal/kgDM) and for growth (*NEg*, Mcal/kgDM) are given by the NRC (2000) as:

$$NEm = 1.37(ME / cj) - 0.138(ME / cj)^2 + 0.0105(ME / cj)^3 - 1.12$$

$$NEg = 1.42(ME / cj) - 0.174(ME / cj)^2 + 0.0122(ME / cj)^3 - 1.65,$$

where cj is a coefficient of unit conversion from calories to joules (cj = 4.184), and ME is the ME value of dietary feed for pre-weaning calves (= 18.4×q_{spl} MJ/kgDM where q_{spl} is the metabolizability of dietary supplemented feed). Thus, the efficiencies of the utilization of ME for maintenance (k_m) and growth (k_g) are expressed as:

$$k_m = NEm / (ME / cj)$$

$$k_g = NEg / (ME / cj).$$

The daily net energy requirements per calf ($NEi_x(t)$, MJ/day) are calculated as:

$$NEi_x(t) = (MEm_x(t) \times k_m + NEg_x(t)) \times cj,$$

where $MEm_x(t)$ is the metabolizable energy requirement for maintenance and $NEg_x(t)$ is the net energy requirement for growth. $MEm_x(t)$ (Mcal/day), $NEg_x(t)$ (Mcal/day), and $ME_x(t)$ (Mcal/day) are estimated according to NARO (2009) as:

$$MEm_x(t) = 0.1067 \times W_x(t)^{0.75}$$

$$NEg_x(t) = (0.008 \times W_x(t)^{0.75} + 1.8) \times DG_x(t)$$

$$ME_x(t) = MEm_m(t) + NEg_m(t) / k_g.$$

Here, the total net energy requirement of calves per cow ($TNE(t)$, MJ/day) is calculated as:

$$TNE(t) = Ncalf(t) \times (NEi_m(t) + NEi_f(t)) \times 0.5,$$

where $Ncalf(t)$ is the number of calves at age t including the effects of pre-weaning survivability, and the sex ratio of calves was set to be 0.5 in this study. The average ME intake from dietary supplemented feed ($TMEspl(t)$, MJ/day) of total calves can be expressed as:

$$TMEspl(t) = 0.5 \times (ME_m(t) + ME_f(t)) \times cj.$$

Thus, the efficiency of the ME utilization of dietary feed for maintenance and production ($kmp(t)$) and its net energy value ($NEspl(t)$, MJ/kgDM) are calculated as follows:

$$kmp(t) = 0.5 \times (NEi_m(t) + NEi_f(t)) / TMEspl(t)$$

$$NEspl(t) = kmp(t) \times 18.4 \times q_{spl}.$$

If $TNE(t)$ is more than the energy value of the milk produced by the cow ($Emilk(t)$, MJ/day), which is calculated from the daily milk yield (*MY*, kg/day) multiplied by the energy value of a unit of milk (*em*, MJ/kg), the amount of dietary feed intake

($TDMspl(t)$, kg/day) and the amount of milk consumption ($Tmilk(t)$, kg/day) can be estimated as:

$$TDMspl(t) = (TNE(t) - Emilk(t)) / NEspl(t)$$

$$Tmilk(t) = MY$$

and if $TNE(t)$ is less than $Emilk(t)$, then

$$TDMspl(t) = 0$$

$$Tmilk(t) = TNE(t) / em\,.$$

The DM intake per calf from dietary feed for male or female calves ($DMspl_x(t)$, kg/day), the DM intake per calf from milk ($DMmilk_x(t)$, kg/day), and the total DM intake per calf from milk and dietary feed ($DMI_x(t)$, kg/day) are calculated as:

$$DMspl_x(t) = TDMspl(t) \times (NEi_x(t) / TNE(t)) / (Ncalf(t) \times 0.5)$$

$$DMmilk_x(t) = Tmilk(t) \times (NEi_x(t) / TNE(t)) / (Ncalf(t) \times 0.5) \times milkdm$$

$$DMI_x(t) = DMspl_x(t) + DMmilk_x(t)\,,$$

where the $milkdm$ is the DM content of a unit of milk (kg/kg).

The TDN intake per calf from dietary feed ($TDNspl_x(t)$, kg/day) is estimated from the difference between the TDN requirement per calf ($TDN_x(t)$, kg/day) and the TDN content of milk consumed per calf ($TDNmilk_x(t)$, kg/day). The values of $TDN_x(t)$, $TDNmilk_x(t)$ and $TDNspl_x(t)$ when $TNE(t)$ is more than $Emilk(t)$ are calculated as:

$$TDN_x(t) = ME_x(t) / 3.62$$

$$TDNmilk_x(t) = DMmilk_x(t) \times milktdn$$

$$TDNspl_x(t) = TDN_x(t) - TDNmilk_x(t)\,,$$

where the $milktdn$ is the TDN content of a unit of milk (kg/kgDM).

DM intake and TDN requirement for steers, heifers and cows after weaning

Estimations of the DM intake and TDN requirement for post-weaning animals are based on NARO (2009). The ME requirement for maintenance and the NE requirement for growth are the same as those for calves (i.e., $MEm_x(t)$ and $NEg_x(t)$, Mcal/day), but the efficiency of the utilization of ME for growth (k_g) is as described in (NARO 2009):

$$k_g = 0.78q + 0.006\,,$$

where q is the metabolizability of feeds, and is assumed to be a fixed parameter for pregnant or lactating cows (=0.6) but set to be variable for steers or non-pregnant heifers ($= 0.4213 + 0.1491 \times DG_x(t)$). For pregnant or lactating cows, additional ME requirements ($MEpreg$ and $MElac$, Mcal/day) are estimated as follows:

- for pregnant cows

$Epreg = 1.542 \times t_c^{5.45601} \times 10^{-12}$

$MEpreg = Epreg / 0.15$

- for lactating cows

$kl = 0.35q + 0.42$

$MElac = 0.815 \times MY(t_m) / kl$,

where *Epreg* is the additional NE requirement for the late pregnant period (MJ/day) (from 222 days to 275 days of pregnancy for Japanese beef cattle), t_c is the days from conception, and *kl* is the efficiency of the utilization of ME for lactation (=0.62).

Finally, the DM intake and TDN requirement are calculated from the sum of the ME requirement ($ME_x(t) = MEm_x(t) + NEg_x(t) / k_g$ ($+ MEpreg + MElact$ in the case of pregnancy or lactation)) (Mcal/day) as:

$DMI_x(t) = ME_x(t) / (4.4 \times q)$

$TDN_x(t) = ME_x(t) / 3.62$.

CP requirement

The CP requirement ($CPR_x(t)$, g/day) is estimated from the net CP requirement ($NP_x(t)$, g/day) when the body weight ($W_x(t)$) is less than 150 kg and is estimated from the calculation of the metabolizable protein (MP) requirement ($MPR_x(t)$, g/day) when $W_x(t)$ is more than 150 kg, according to NARO (2009).

- for calves ($W_x(t)$ < 150 kg)

The fecal nitrogen ($FN_x(t)$, g/day) and the efficiency of conversion from $NP_x(t)$ to $CPR_x(t)$ (EP) are assumed to vary according to the change in $W_x(t)$ as follows:

when $W_x(t)$ < 50 kg, $FN_x(t) = 2.00 \times DMI_x(t)$ and $EP = 0.75$,

when $W_x(t)$ < 100 kg, $FN_x(t) = 3.02 \times DMI_x(t)$ and $EP = 0.66$,

and when $W_x(t)$ < 150 kg, $FN_x(t) = 4.32 \times DMI_x(t)$ and $EP = 0.56$.

In order to calculate $NP_x(t)$, the urinary nitrogen ($UN_x(t)$, g/day), the scurf losses of protein ($SP_x(t)$, g/day), and the retained protein ($RP_x(t)$, g/day) are estimated as:

$UN_x(t) = 0.44 \times W_x(t)^{0.5}$

$SP_x(t) = 0.2 \times W_x(t)^{0.6}$

$RP_x(t) = 188 \times DG_x(t)$.

Then $NP_x(t)$ is calculated as:

$NP_x(t) = (FN_x(t) + UN_x(t)) \times 6.25 + SP_x(t) + RP_x(t)$,

and finally, $CPR_x(t)$ is estimated as:

$CPR_x(t) = NP_x(t) / EP$.

In a similar fashion with the TDN intake per calf, the CP intake per calf from dietary feed ($CPRspl_x(t)$, g/day) is estimated from the difference between CP requirement per calf ($CPR_x(t)$, g/day) and CP content of milk consumed per calf ($CPmilk_x(t)$, g/day), and is calculated as:

$$CPmilk_x(t) = DMmilk_x(t) \times milkcp$$

$$CPRspl_x(t) = CPR_x(t) - CPmilk_x(t),$$

where the *milkcp* is the CP content of a unit of milk (g/kgDM).

- for steers, heifers and cows ($W_x(t)$ > 150 kg)

The calculations for $UN_x(t)$ and $SP_x(t)$ are same as those for calves ($W_x(t)$ < 150 kg), but the equations for $FN_x(t)$ and $RP_x(t)$ are changed as:

$$FN_x(t) = 4.80 \times DMI_x(t) - (130 \times TDN_x(t) \times 0.64 \times 0.25 \times 0.5) / 6.25$$

$$RP_x(t) = (235 - 0.293 \times W_x(t)) \times DG_x(t).$$

The MP requirements for maintenance ($MPm_x(t)$, g/day) and for growth ($MPg_x(t)$, g/day) are calculated as:

$$MPm_x(t) = ((FN_x(t) + UN_x(t)) \times 6.25 + SP_x(t)) / kp_m$$

$$MPg_x(t) = RP_x(t) / kp_g,$$

where kp_m and kp_g are the efficiencies of the utilization of protein for maintenance and for growth, and are set to be 0.67 and 0.492, respectively. Consequently, $MPR_x(t)$ is calculated as:

$$MPR_x(t) = MPm_x(t) + MPg_x(t).$$

Furthermore, the microbial CP ($MCP_x(t)$, g/day), the degradable MP by ruminal microorganisms ($MPd_x(t)$, g/day), and the undegradable MP ($MPu_x(t)$, g/day) are estimated as:

$$MCP_x(t) = 130 \times TDN_x(t),$$

$$MPd_x(t) = 0.8 \times 0.8 \times MCP_x(t),$$

$$MPu_x(t) = MPR_x(t) - MPd_x(t).$$

Here, the conversion efficiencies of the rumen degradable protein ($RDP_x(t)$, g/day) to $MCP_x(t)$ and the rumen undegradable protein ($RUP_x(t)$, g/day) to $MPu_x(t)$ are assumed to be 0.85 and 0.80, respectively, and the recycling CP is assumed to be 15% of $CPR_x(t)$. Then $CPR_x(t)$ is calculated as:

$$CPR_x(t) = MCP_x(t) / 0.85 + MPu_x(t) / 0.80 - CPR_x(t) \times 0.15,$$

and therefore,

$$CPR_x(t) = (MCP_x(t) / 0.85 + MPu_x(t) / 0.80) / 1.15.$$

When $MPR_x(t)$ is evaluated for the calculation of $CPR_x(t)$, additional MP requirements (*MPpreg*, *MPlac*, g/day) are accounted for pregnant and lactating cows, respectively, as follows:

-- for pregnant cows

$$Ppreg = BW / 40 \times 10^{3.707-5.698\times\exp(-0.00262\times t_c)} \times 34.37 \times \exp(-0.00262 \times t_c)$$

$$MPpreg = Ppreg / 0.65$$

-- for lactating cows

$$MPlac = 0.041 \times MY(t_m) \times 1000 / 0.65,$$

where BW is the mean birth weight of calves per calf (= $0.5 \times (BW_m + BW_f)$), *Ppreg* is the dairy retained protein in uterus for the late pregnant period (g/day) (from 222 days to 275 days of pregnancy for Japanese beef cattle) and t_c is the days from conception. The milk protein content for Japanese Black cows is assumed to be 4.1%.

Calcium and phosphorus requirements

- for pre-weaning calves

The calcium (Ca) and phosphorus (P) requirements ($CAR_x(t)$, $PHR_x(t)$, g/day) and the Ca and P intakes from dietary feed ($CAspl_x(t)$, $PHspl_x(t)$, g/day) are estimated as follows:

$$CAR_x(t) = DMspl_x(t) / DMI_x(t) \times (0.0154 \times W_x(t) + 0.071 \times RP_x(t)) / 0.50 + DMmilk_x(t) / DMI_x(t) \times (0.0154 \times W_x(t) + 0.071 \times RP_x(t)) / 0.95$$

$$PHR_x(t) = DMspl_x(t) / DMI_x(t) \times (0.0280 \times W_x(t) + 0.039 \times RP_x(t)) / 0.85 + DMmilk_x(t) / DMI_x(t) \times (0.0280 \times W_x(t) + 0.039 \times RP_x(t)) / 0.94$$

$$CAspl_x(t) = DMspl_x(t) / DMI_x(t) \times (0.0154 \times W_x(t) + 0.071 \times RP_x(t)) / 0.50$$

$$PHspl_x(t) = DMspl_x(t) / DMI_x(t) \times (0.0280 \times W_x(t) + 0.039 \times RP_x(t)) / 0.85,$$

where $W_x(t)$ is the body weight (kg) and $RP_x(t)$ is the retained protein (g/day).

- for post-weaning steers, heifers and cows

$CAR_x(t)$and $PHR_x(t)$are estimated as:

$$CAR_x(t) = (0.0154 \times W_x(t) + 0.071 \times RP_x(t) + 1.23 \times MY(t_m) + 0.0137 \times W_c(t_c)) / 0.50$$

$$PHR_x(t) = (0.0280 \times W_x(t) + 0.039 \times RP_x(t) + 0.95 \times MY(t_m) + 0.0076 \times W_c(t_c)) / 0.85,$$

where $MY(t_m)$ is the dairy milk yield (kg/day) and $W_c(t_c)$ is the total weight of the conceptus (kg) in the case of lactation and/or pregnancy.

Appendix B - Calculations of mortality and reproduction, and explanation of the herd composition dynamics

1. Mortality and reproductive traits

The mortalities of calves ($dcmort$) and cows ($dmort$) per day are calculated as:

$$dcmort = 1-(1-cmort)^{(1/t_{wean})}$$

$$dmort = 1-(1-mort)^{(1/365)},$$

where $cmort$ is the pre-weaning calf mortality rate, $mort$ is the annual mortality rate after weaning and t_{wean} is the weaning age.

The conception rate of cows ($Cr(n)$) per service in each parity is calculated using a quadratic function estimated from Rogers (1972) as:

$$Cr(n) = (-0.705n^2 + 6.264n + 80.159)/100 \ (R^2 = 0.95)$$

where n indicates the number of parity. The $Cr(n)$ peaks in the 3rd parity and declines subsequently. The effect of differences in feeding level on the conception rate is not taken into account in the function, because the feed quantity is estimated from the nutrient requirements in the model and is assumed to be sufficient for mating. In the present study, the average period from parturition to the next conception for all females at parity n ($T_{do}(n)$, days) is expressed as the sum of the anoestrus postpartum interval (t_{pp}, days) and the average of mating trial period at parity n, in accordance with the procedure of Bailie (1982). The number of females that fail to conceive after i oestrous cycles decreases by $(1-Cr(n))^i$, and the corrected calving rate ($CCr(n)$) and $T_{do}(n)$ are calculated as:

$$CCr(n) = calvr \times (Cr(n) + Cr(n)(1-Cr(n)) + Cr(n)(1-Cr(n))^2 + \cdots Cr(n)(1-Cr(n))^{(mt-1)})$$

$$= calvr \times Cr(n) \times \sum_{i=1}^{mt}(1-Cr(n))^{i-1}$$

$$T_{do}(n) = (t_{pp} - t_{op}) + t_{op} \times Cr(n) + 2 \times t_{op} \times Cr(n)(1-Cr(n)) + 3 \times t_{op} \times Cr(n)(1-Cr(n))^2 + \cdots$$

$$= (t_{pp} - t_{op}) + t_{op} \times \sum_{i=1}^{mt} i(1-Cr(n))^{i-1},$$

where $calvr$ is the calving rate, t_{op} (days) is the mean length of the oestrous cycle and for first mating, t_{pp} is equal to the sum of the weaning and post-weaning periods, i.e., the age at first mating (t_{mtfst}, days), and mt is the number of mating trials. It is then assumed that females in parity n conceive on the same day represented by $T_{do}(n)$.

Finally, the calving interval $T_{cl}(n)$ (days) is defined as the period between parturitions and is the sum of $T_{do}(n)$ and the gestation length (t_{preg}, days) as:

$T_{cl}(n) = T_{do}(n) + t_{preg}$.

In the present study, $cmort$, $mort$, t_{wean}, t_{pp}, $calvr$, t_{op}, t_{mtfst}, mt, and t_{preg} are treated as fixed parameters (see Table 1).

2. Herd composition dynamics

In the present study, the simulation is performed assuming that the number of replacement heifers at the start of simulation is 1.0. From this number, the $N(pa,n)$ matrix is calculated, which indicates the number of cows at reproduction time n when the cows are kept until culling parity pa ($n \le pa$). The $N(pa,n)$ matrix is calculated with the mortality and the corrected calving rate ($CCr(n)$) as follows:

$$N(pa,1) = (1.0 \times (1 - cmort) \times (1 - dmort)^{(t_{mtfst} + Tcl(1) - t_{wean})}) \times CCr(1)$$

$$N(pa,n) = (N(pa,n-1) \times (1 - dmort)^{Tcl(n)}) \times CCr(n).$$

Using this matrix, the total number of newborns ($Tnb(pa)$) and replacement rate of cows ($rep(pa)$) are expressed as:

$$Tnb(pa) = \sum_{i=1}^{pa} N(pa,i)$$

$$rep(pa) = 1.0/(0.5 \times Tnb(pa)).$$

The denominator of the expression of $rep(pa)$ theoretically represents the sum of female calves when the sex ratio is 0.5. Using $N(pa,n)$ and $rep(pa)$, the numbers of newborn male calves ($Ncalf_m(pa,n)$) and non-replacement newborn female calves ($Ncalf_f(pa,n)$) born from cows at the n-th parity are:

$$Ncalf_m(pa,n) = 0.5 \times N(pa,n)$$

$$Ncalf_f(pa,n) = (1 - rep(pa)) \times 0.5 \times N(pa,n).$$