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Life Cycle Assessment of Alternative Swine Management Practices

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Life Cycle Assessment of Alternative Swine Management Practices

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by

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Abstract

Life Cycle Assessments (LCAs) are quantitative analyses of complex systems for evaluation of impacts and risk associated with management decisions. LCAs can be effective tools for determining comparative advantages of management strategies across specific impact concern. In this study, life cycle assessments of pork production management alternatives was performed. The alternative management practices included in this study were production of entire males (boars), use of pens for gestation housing, immunocastration, production without growth promoting antimicrobials, production without growth promoting and preventive antimicrobials, and production without ractopamine. These LCAs evaluated the impact of each management strategy on greenhouse gas emission (GHG), cumulative energy use, and cumulative water use compared to the common baseline. Each alternative management strategy was simulated in Pig Production Environmental Footprint (PPEF) model by varying key variables. Life cycle inventory inputs for unit process created using PPEF model were used for SimaPro V7.3 (Pre' Consultants, The Netherlands), an LCA modeling program. The functional unit for the analysis was one kilogram live weight at the farm gate. Influence of temperature on impact categories was evaluated by testing all alternate management practices at five temperature regimes. While, temperature influenced the changes to the impact categories, hypothesis testing was performed for alternative management practices for scenario at Wright County, Iowa that used typical meteorological year to control temperature inside the barn. LCAs of alternative management practices yielded a range of results. Increase in GHG emissions, cumulative energy use, and cumulative water use were observed for no growth promoting antimicrobials (1.559, 1.746, and 1.038% respectively), no growth promoting or preventive antimicrobials (17.321, 18.399, and 15.577% respectively), and removal of ractopamine (6.515, 4.867, and 7.518%

respectively) scenarios. For entire males scenarios GHG emission and cumulative energy use increased by 2.092 and 3.748% but cumulative water use decreased by 2.294%. Lower GHG emissions, cumulative energy use, and cumulative water use were observed for gestation pens (0.973, 1.499, and 0.972% respectively) and immunocastration (2.385, 2.567, and 2.963% respectively) scenarios. These changes could be concluded with at least 75% confidence only for lower water consumption for entire males, decreased GHG emissions and water consumption for immunocastration, increased cumulative energy consumption for no growth promoting antimicrobials, increase in all three impact categories for no growth promoting or preventive antimicrobials, and increased GHG emissions, cumulative energy and cumulative water consumption for removal of ractopamine scenarios. A null hypothesis that changing management practices in the pork production in the US does not affect impact category metrics used for sustainability assessment was rejected using one tailed paired t-test at $P < 0.001$. However, it is important to understand that these results are the product of simulation of pork production strategies combined with the unit process LCAs and considering possibilities of uncertainties in the model and life cycle inventory, these results should be interpreted with caution. Results of this study should be interpreted as general trend, rather than absolute numbers observed in this study.

Acknowledgments

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Chapter 1 Introduction

There is an increasing awareness of the need to evaluate the sustainability of pork production systems using a systems level analysis. Pork producers in the US are facing unprecedented pressure from special interest groups, regulatory agencies and supply chain customers to demonstrate improvements across sustainability metrics and animal welfare. This demands for changes to some of the management practices prevalent in the swine industry and attempts are made in this direction. Florida, in 2002, banned use of sow gestation crates through voter referendum process and similar ban was imposed on the swine industry in Arizona in 2006 (Mench 2008). A survey conducted by the Rutgers University in 2003 revealed that between 74 and 83% of the participants disagreed with practices such as tail docking of cows and pigs without analgesics and confining gestating sows respectively (Mench 2008). Heeding to its consumers, Smithfield Foods decided in 2007 to phase out gestation stalls on company-owned farms over next 10 years and replace them with pens. However, it is important to understand that even smallest changes made to the production might sometimes have huge environmental impacts. If the changes to the management practices were made on the basis of single measurement criteria, it could result in undesirable outcomes across other metrics. Therefore, assessment of impact changes associated with changes made to the production practices is necessary to make sure we move forward towards making agriculture more sustainable. Life cycle assessment has been proved to be a powerful tool for this assessment.

Life cycle assessment

Life Cycle Assessments (LCA) provide quantitative, confirmable, and manageable models to evaluate production processes, analyze options for innovation, and improve understanding of complexity in agricultural production systems. A LCA can identify areas where process changes potentially enabled by new research and development, can significantly reduce the associated impacts. Broadly, LCA consists of four stages:

1. Define the goal and scope;
2. Conduct life cycle inventories (collection of data needed to perform the necessary calculations);
3. Perform impact assessment;
4. Analyze and interpret the results.

Life Cycle Assessment has the potential to foster changes in agricultural practices that lead to environmental, social, and economic improvements, the so-called triple bottom line. Life cycle assessment in the swine industry holds the promise of identifying inefficiencies in the system and changes to the sustainability metrics resulting from possible changes to the management practices, which can be addressed to foster the long-term health of the industry. This project supports the goal of the National Pork Board environment committee to: optimize management practices to enable producers to make informed management practice decisions to continually improve their farms; provide pork producers with the information and education they need to evaluate and implement appropriate management practices on their farms; and educate customers about the environmental and sustainability consequences of their purchase decisions.

The structure of an LCA is determined by its purpose. The scope of LCAs can be as broad as "*all material and energy inputs and outputs of a process or product*" to *"water use in production of cotton fabric from raw cotton."* The scale of the purpose defines the scale of the analysis. In this study a comparative LCA for pork management practices was conducted with scope of LCA restricted to cradle through farm gate.

Objective of the study

The objective of this study was to quantify differences or establish the absence of differences in greenhouse gases (GHG), cumulative energy use, and water consumption between current practices and proposed alternate management system in the US pork production.

Scope of the work

This study analyzed greenhouse gas emissions, cumulative energy use, and water consumption from different management practices (Table 1.1). The scope of the study was restricted to cradle (crop and fuel production) through farm gate. In 2011, commercial hog slaughter totaled 110.9 million head, 1% higher than 2010 with 99.2% of the hogs slaughtered under federal inspection. The average live weight was up 1.36 kg (3 lb.) from 2010 at 124.74 kg (275 lb.). Barrows and gilts comprised 96.6% of the total federally inspected hog slaughter and total pork slaughter in federally inspected commercial facilities reported by NASS Quickstat in 2013 was 10.45 billion kg (23.04 billion lb).

Table 1.1- Alternate management practices evaluated in this study

Management strategy	Description
Immunocastration	Use of immunocastration methods/product(s)- Improvest®
No ractopamine	Removal of ractopamine (RAC) as a tool to improve growth and production
No GP antimicrobials	Removal of antimicrobials as growth promoters (GP)
No Prev. antimicrobials	Removal of antimicrobials to prevent emergence of herd infection in addition to removal of GP antimicrobials
Pen gestation	Use of pen gestation housing
Boars	Split sex management without surgical- or immune-castration

Problem statement

There is increased awareness about sustainability in the agriculture and animal production and demand from the animal welfare groups demand changes to some of the management practices in the pork production. However, it would not be wise to make changes to the production practices without assessing the possible impacts of those changes on the sustainability metrics.

Hypothesis

The purpose of this research is outlined by the null hypothesis

H_o: *Changing management practices in the pork production in the US does not affect impact category metrics used for sustainability assessment*

An alternate hypothesis was defined as

H_a: *Changing management practices in the pork production in the US affects impact category metrics used for sustainability assessment*

Chapter 2 Literature review

Immunocastration

Castration of male pigs is performed to avoid boar taint in the meat, improve the meat quality and to reduce aggressive behavior in swine. Boar taint is a result of skatole levels higher than 0.2 μg g^{-1} of fat in pork (Dunshea et al. 2001; Morales et al. 2010; Thun et al. 2006). Surgical castration (SC) of male pigs is usually performed without anesthesia within first 1 to 2 weeks of life (FAO ; Thun et al. 2006). While this technique efficiently eliminates boar taint in the meat, it raises concerns for animal welfare as the procedure causes pain and distress in pigs (Morales et al. 2010). An alternative technique developed to avoid boar taint and aggressive behavior in male pigs without surgical castration is immunocastration (IC). In this procedure, pigs are administered two injections of an analog of gonadotropin-releasing hormone (GnRH) that causes the animal's immune system to create antibodies against GnRH and down regulate the skatole production pathways. One of the GnRH analog compounds is marketed as Improvac® (also called Improvest®) developed by Pfizer Pharmaceuticals Inc., which is administered at about 9 weeks of age and then again at least 4 weeks after the primary dose (Pfizer Animal Health). Pfizer recommends slaughtering the pigs between third and tenth week following the second dose to avoid boar taint.

Batorek et al. 2012a conducted a statistical analysis of data collected from 41 published articles, which revealed that IC effectively reduced reproductive activities and concentrations of substances causing boar taint. Immunocastration showed a statistically significant positive effect on the performance of the pigs with improved average daily gain (ADG) and feed efficiency (FE). Until the second injection, the male pigs performed similar to boars, that is improved gain and FE compared to surgically castrated barrows. After second vaccination however, their performance was more like barrows. The daily feed intake of the pigs increased after second vaccination and feed efficiency declined. The ADG for IC was slightly higher than observed for boars.

Similar changes in the performance of IC pigs have been reported by other researchers. In most of the studies, weights and feed intake of the pigs were monitored for the period between the first vaccination and slaughter and the performance parameters were reported for times between the first and second vaccination and between the second vaccination and slaughter or also between the first vaccination and slaughter. Higher ADGs in IC pigs compared to SC were reported in most of the studies for the study period between second injection and slaughter (Batorek et al. 2012a; Fabrega et al. 2010; Font-i-Furnols et al. 2012; Morales et al. 2010; Morales et al. 2011; Skrlep et al. 2012; Skrlep et al. 2010a; Skrlep et al. 2010b; Zamaratskaia et al. 2008). The daily feed intake for IC pigs however, varied during the same observation period. Batorek et al. (2012b); Morales et al. (2011); Skrlep et al. (2010b); Zamaratskaia et al. (2008) observed lower DFI in IC pigs compared to SC during the study period between second injection and slaughter, while Fabrega et al. (2010); Morales et al. (2010) reported higher DFI. Feed efficiency however, was consistently better in IC pigs for the study period between second injection and slaughter compared to SC, mainly due to improved ADG (Batorek et al. 2012a; Dunshea et al. 2011; Fabrega et al. 2010; Morales et al. 2010; Morales et al. 2011; Skrlep et al. 2010b). On an average for study periods between second injection and slaughter, performance of IC pigs was better compared to SC pigs, with 13.16% higher ADG and 12.49% higher FE. The DFI however, was 3.23% higher in IC pigs. The averages of data obtained from Andersson et al. (2012); Batorek et al. (2012a); Dunshea et al. (2011); Fabrega et al. (2010); Font-i-Furnols et al. (2012); Morales et al. (2010); Morales et al. (2011); Skrlep et al. (2012); Skrlep et al. (2010b);

Zamaratskaia et al. (2008) produced the ADG of 1.04 kg d^{-1}, DFI of 3.31 kg d^{-1}, and FE of 0.32 for IC pigs for study period between second injection and slaughter. The performance parameters for SC pigs during same study duration were 0.91 kg d^{-1}, 3.2 kg d^{-1}, and 0.29 for ADG, DFI, and FE respectively.

Between first and second injection SC pigs showed higher average ADG (Andersson et al. 2012; Batorek et al. 2012a; Fabrega et al. 2010; Font-i-Furnols et al. 2012; Morales et al. 2010; Morales et al. 2011; Skrlep et al. 2012; Skrlep et al. 2010b; Zamaratskaia et al. 2008). However, IC pigs, on an average had lower DFI during this study period leading to higher FE. When compared for the overall study period between first injection and slaughter, IC pigs showed higher ADG, lower DFI, and therefore improved FE (Dunshea et al. 2001; Fabrega et al. 2010; Millet et al. 2011; Morales et al. 2010; Morales et al. 2011; Weiler et al. 2013b; Zamaratskaia et al. 2008). The higher ADG observed in IC pigs, mostly after second injection, was attributed to reduced sexual and aggressive behavior in pigs. Immunocastration also reduced concentration of compounds such as skatole and androstenone, responsible for boar taint, below the detection level in the fatty tissue of pigs (Andersson et al. 2012; Batorek et al. 2012a; Dunshea et al. 2001; Font-i-Furnols et al. 2012; Jaros et al. 2005; Morales et al. 2010; Pauly et al. 2009; Skrlep et al. 2012; Skrlep et al. 2010b; Weiler et al. 2013a; Zamaratskaia et al. 2008).

Immunocastration also influenced carcass percentage and lean dressing percentage in pigs. While average carcass percentage in IC pigs was 1.82% lower compared to SC pigs (IC- 75.35%, SC- 77.13% for SC), the lean meat percentage was 1.32% higher in IC pigs (IC- 55.48%, SC- 54.16%) (Andersson et al. 2012; Batorek et al. 2012b; Dunshea et al. 2011; Dunshea et al. 2001; Font-i-Furnols et al. 2012; Morales et al. 2010; Pauly et al. 2009; Skrlep et al. 2012; Skrlep et al. 2010a; Zamaratskaia et al. 2008). An increased lean meat in immunocastrated pigs was a result of higher ham and shoulder percentages compared to loin (Pauly et al. 2009).

For period between first vaccination and slaughter, (Morales et al. 2010) reported higher numerically ADG for IC pigs (0.845 kg d^{-1}) over the study duration compared to both surgically castrated pigs (0.824 kg d^{-1}) and entire males (0.823 kg d^{-1}). Higher values of ADG were also reported for time period between first and second injection (IC- 0.809 ± 0.0227, SC- 0.808 ± 0.0226, EM- 0.776 ± 0.0225 kg d^{-1}) and between second injection and slaughter for IC pigs (IC- 0.951 ± 0.264, SC- 0.879 ± 0.0263, EM- 0.771 ± 0.0261 kg d^{-1}). IC pigs showed higher statistically significant feed efficiency (0.39) compared to SC pigs (0.36) for overall study period.

Antimicrobial use

Although using antimicrobials to successfully improve growth performance in livestock and prevent and control diseases dates back to over five decades, there is a growing concern about potential antimicrobial resistant microorganisms affecting human health (Turner et al. 2001). If the restrictions over the antimicrobial use in the animal diet were imposed in the United States, estimating the downstream effects of these restrictions on carbon footprint, energy use and water use through life cycle analysis would become necessary.

Antimicrobials are used in swine production for growth promotion in the nursery phase and for prevention of epidemics and endemics in grow-finish barns, as well as for treating sick pigs. Most of the researchers studying absence of antimicrobials in the swine diet focused on antimicrobials use in the nursery barns for growth promotion. In these studies pigs supplemented with antimicrobials or alternatives to antimicrobials were compared with control group. The pigs in the control groups did not receive any antimicrobials. Studies testing antimicrobial alternatives compared pigs supplemented with alternatives to antimicrobials to control group and to pigs on antimicrobials. Our study mainly focused on antimicrobials and therefore, data relevant to antimicrobials were obtained from the published researches.

The National Pork Board (NPB) task force as well provided data to evaluate two scenarios with potential effects of reducing or eliminating antimicrobials on pig growth. The first scenario described effects data for impacts of eliminating growth promoting (GP) antimicrobials use, while the second scenario described effects on production from eliminating both growth promoting and preventive antimicrobials. The NPB task force estimated 5% decrease in ADG of pigs in nursery and 3% in grow-finish barn for median health facilities without GP antimicrobials in production. Feed efficiency was expected to decrease by 3.5 and 2% in nursery and grow-finish barns respectively.

Similar results were also reported by other researchers. In most of the research studies, not using antimicrobials in the nursery phase resulted in lower ADG, lower FE, and lower DFI in pigs (Choi et al. 2011; Dritz et al. 2002; Gottlob et al. 2007; Hahn et al. 2006; Keegan et al. 2005; Kiarie et al. 2011; Lee et al. 2012; Li et al. 2008; Shen et al. 2009; Wang et al. 2011; Yoon et al. 2013). However, in one of the three experiments Keegan et al. (2005) conducted, using carbadox, a type of antimicrobial, did not improve the ADG in pigs and the DFI was unchanged compared to the control group. The authors could not explain the results. They however concluded that antimicrobial alternatives tested in the studies were not as effective as the antimicrobials in the diet.

On an average, over an entire study period the ADG and FE in pigs treated with antimicrobials was 14 and 8% higher respectively compared to control group (Choi et al. 2011; Dritz et al. 2002; Gottlob et al. 2007; Hahn et al. 2006; Keegan et al. 2005; Kiarie et al. 2011; Lee et al. 2012; Li et al. 2008; Shen et al. 2009; Wang et al. 2011; Yoon et al. 2013). Average DFI over an entire study period was 10% higher as well in pigs treated with antimicrobials. Averages of the data obtained from (Choi et al. 2011; Dritz et al. 2002; Gottlob et al. 2007; Hahn et al. 2006; Keegan et al. 2005; Kiarie et al. 2011; Lee et al. 2012; Li et al. 2008; Shen et al. 2009; Wang et al. 2011; Yoon et al. 2013), resulted in ADG of 0.38 kg d^{-1}, DFI of 0.49 kg d^{-1}, and FE of 0.72 in pigs treated with antimicrobials, compared to ADG, DFI and FE of 0.33 kg d^{-1}, 0.46 kg d^{-1}, and 0.67 respectively in pigs reared without antimicrobials. Enhanced growth performance with antimicrobials was attributed to improved nutrient digestibility in pigs (Hahn et al. 2006).

The NPB task force also estimated that no using GP antimicrobials could mean fewer pigs would reach the expected weight and size requirements in the production facility, which was estimated to increase voluntary cull rate in nursery and grow-finish barn to 0.25% for median health facilities. Without GP, the mortality rate was expected to increase by 0.2% in the nursery phase. Because GP is used mostly in nursery phase, production without GP antimicrobials was expected to have no impact on mortality rates in grow-finish barn. No change due to loss of GP was anticipated on other performance factors such as diet formulation, water consumption or, and average vet visits.

The scenario defined by the NPB task force provided data for production of pigs without use of either GP or preventive antimicrobials. When herd health is trending downward antimicrobials are used prophylactically to reduce the chance of herd-wide infection. Animals which become sick are treated therapeutically and will recover or die. Without preventive use, more animals are likely to need therapeutic doses. The NPB task force estimated 7% decrease in ADG in both nursery and grow finish barns without GP and preventive antimicrobials for a median health facility. Low health status of animals in this case, was expected to result in estimated reduction in FE by 6 and 5% for nursery and grow finish barns respectively. Voluntary cull rates and mortality was estimated to increase by 4% in nursery and by 5 and 5.5% respectively in grow-finish bar.

None of the research studies reviewed for current study, included experiments to estimate effects of production without both GP and preventive antimicrobial use in the grow-finish barn. Effects of production without antimicrobials on the voluntary cull rate and mortality in pigs was not explored in these studies as well.

Ractopamine

Ractopamine hydrochloride (RAC) is a dietary supplement, which improves ADG, FE, and lean meat yield in finishing pigs (Armstrong et al. 2004; Barbosa et al. 2012; Dunshea et al. 1993; Hinson et al. 2011). With improved FE and ADG in pigs, finishing floors can be turned about 1 week sooner with RAC supplementation to pigs (Patience et al. 2009). The task force convened by the NPB suggested using RAC for last 28 days in pig production finishing cycle at the weight basis concentration of 6.75 g/T of feed. Without RAC total annual pork production may decrease as the result of decreased ADG and FE in pigs (Hosteler et al. pers. Comm., 2012).

Hosteler et al. (pers. Comm, October 2012) estimated that without RAC, ADG in adult pigs would decrease by 12.5% and average DFI would increase by about 1.7%. Increased DFI and reduced ADG would decrease feed efficiency by 13.5%, compared to RAC supplementation and the pigs might take four additional days to reach the market weight.

These estimates were in agreement with other studies reviewed. The research material reviewed for the present study investigated the effects of production without RAC on pig performance at different concentrations of RAC in the diet and for different feeding regimens as well. In most of the studies without RAC supplementation growth performance of the pigs decreased. While effects of RAC free production were studied in the reviewed researches on SC, IC, entire males (EM), and gilts, this study focused only on RAC removal in SC pigs.

Both RAC level in the diet and days for which RAC was supplemented influenced pig performance. When compared to pigs fed 5 ppm of RAC through the diet, an average ADG, DFI, and FE in control pigs decreased by 8%, 1%, and 5% respectively (Armstrong et al. 2004; Armstrong et al. 2005; James et al. 2013; Lanferdini et al. 2013; Main et al. 2009; Patience et al. 2009; Ross et al. 2011; SMITH et al. 1995). Except for Smith et al. (1995) and Patience et al. (2009) pigs were supplemented with 5 ppm of RAC for between 21 and 28 days. Patience et al. (2009) reported 12% and 11% higher ADG and FE respectively, compared to control pigs, in pigs supplemented with 5 ppm of RAC for 42 days with 0.3% lower DFI.

At diet RAC level of 10 ppm average ADG and FE in pigs supplemented with RAC was 12% higher, while DFI was 0.8% lower compared to control pigs (Almeida et al. 2013; Armstrong et al. 2004; Barbosa et al. 2012; Barker et al. 2005; Crome et al. 1996a; James et al. 2013; Main et al. 2009; Mitchell 2009; Ross et al. 2011; See et al. 2004). When pigs performance averages was compared at 20 ppm of diet RAC level, ADG and FE were 12 and

18% higher with RAC supplementation and the DFI was 4% lower (Armstrong et al. 2004; Crome et al. 1996b; Dunshea et al. 1993; SMITH et al. 1995).

Besides improving growth performance RAC, a β-agonist, also increases protein deposition in pigs by binding to β-receptors on the cell membrane and increasing muscle fiber size (Moore et al. 2009). When averages were calculated using data obtained from review material, carcass yield and lean percentage were 0.9 and 1% higher with RAC supplementation at 10 mg kg^{-1} weight basis concentration (Almeida et al. 2013; Armstrong et al. 2004; Barbosa et al. 2012; Crome et al. 1996a; Main et al. 2009; See et al. 2004).

Almeida et al. (2013)evaluated time-dependent influence of RAC supplementation in finishing pigs and found that ADG and FE of pigs is positively influenced by RAC feeding duration with maximum improvement in growth performance achieved during first 21 days of RAC feeding. Average daily gain in pigs supplemented 10 mg kg^{-1} of RAC improved from 0.8 to 7% when feeding duration was increased from 7 to 21 days. Feed efficiency during these feeding durations improved from 5 to 11%. When RAC supplementation was continued further for 7 more days ADG and FE were 5 and 9% higher respectively compared to control pigs. Feeding duration also influenced carcass percentage and lean meat percentage in pigs, with carcass and lean meat percentages increasing with longer feeding duration.

Gestation housing

Gestation stalls used for sow provides maximum barn space utilization density and allows individual monitoring and controlled feeding (Lammers et al. 2007). However, this method is under scrutiny because gestation stalls do not allow sows free movement (Lammers et al. 2007). At the same time sows housed in group pens are prone to injuries due to aggression resulting in stress and injury. When data obtained from the published articles were studied, the differences between sows housed in gestation stalls and in group pens were observed in number of live births, litter size, pre-weaning mortality, and piglet weights at birth. Lammers et al. (2007) observed statistically significant difference in number of piglets born alive and number of stillborn piglets between sows housed in stalls and group hoop barns. The number of piglets born alive was 10 and 9.2 for group and individual stalls respectively. While the litter size did not change much (11.3 for stalls and 11.7 for group), higher number of stillborn piglets were observed for stalls (2.0) compared to group (1.7). Pre-weaning mortality however, was higher for group housing (15%) compared to gestation stalls (14%).

Slightly different results were reported by McGlone et al. (2004), in their meta-analysis of gestation housing. The authors reported no significant differences between use of stall or pens for gestation housing in terms of litter characteristics. The authors also reported numerically lower piglets born alive per litter (9.9 for stalls and 9.8 for pens), and smaller litter size (10.8 for stalls, 10.5 for pens) in sows housed in group pens. Number of piglets stillborn however, was higher for stalls (0.71) compared to group (0.63).

When data obtained from published articles were averaged, litter size and number of piglets born alive were 1.5 and 1.46% higher for stalls compared to group housing. Number of stillborn piglets was 17% lower, while pre-weaning mortality was 1.2% higher (Anil et al. 2005; Bates et al. 2003; Harris et al. 2006; Jansen et al. 2007; Lammers et al. 2007; McGlone et al. 2004; SCHMIDT et al. 1985; Weng et al. 2009).

Munsterhjelm et al. (2008) and Salak-Johnson et al. (2007) reported differences in the back fat thickness as well between sows in group and stalls, with deeper back fat thickness observed for sows kept in pens.

Effect of gestation housing was also reported on ability of sows to receive successful insemination. Bates et al. (2003) reported that 72% of sows housed in group returned to estrus within 7 days compared to 68.4% of sows in gestation stalls. In addition 94.3% of group housed sows remained pregnant after initial service compared to 89.4% sows in stalls

2.5 Description of Models

Assessment and comparison of different management practices in terms of greenhouse gas emissions, water use and electricity use involved a two-step process. In the first step nursery, grow-finish and sow barns were simulated using Pig Environmental Footprint model (University of Arkansas). The outputs of this model were used in the second step for LCA analysis using SimaPro V7.3 (Pre' Consultant, the Netherlands).

Pig Environmental Footprint model

The growth and feed conversion performance of pigs, resource consumption, and emissions to the environment were simulated using the Pig Production Environmental Footprint model (PPEF model) developed at the University of Arkansas. The Pig Environmental Footprint model uses mathematical relationships to simulate pig growth, feed intake and water consumption, electricity and natural gas use, manure handling, and greenhouse gas emissions during each production cycles. The PPEF model has an ability to simulate pig production at both barn and facility level and includes grow barn, sow barn, gestation barn, and farrowing barn. The sow barn is considered as gestation and farrowing barn together. The PPEF model uses a growth prediction model developed by the National Resources Council (NRC) to predict growth and feed consumption of pigs in both grow and sow barn (NRC, 2012).

NRC growth model

A growth model developed by National Research Council (2012) is a daily time step model, which is a function of weight of pigs on previous day and metabolizable energy (ME) of feed available to the pigs. The growth model for grow-finish pigs is sensitive to the ambient temperature in the barn and accounts for temperature, floor space per pig, sex of the pig, and physical capacity of pigs to ingest the feed. Depending upon the factors mentioned above, the model predicts possible metabolizable energy intake (MEI) and maintenance metabolizable energy requirement (MMER) in pigs. The MMER is the energy required for maintenance of body tissue and body functions. The MEI in excess of MMER is used for protein and lipid deposition in the body. Besides daily protein and lipid deposition, the model also predicts water and ash content of the body, which when combined with protein and lipid content gives empty body weight (EBW). Body weight at the end of the day is then calculated using EBW and gut fill (Appendix A: National Research Council model for growth of grow-finish pigs implemented in Pork Production Environmental Footprint (PPEF) model). Daily feed intake of the pigs is then simply the ratio of MEI and diet ME content. The fat free lean content of the meat is estimated as a function of probe backfat thickness, live body weight of pig and carcass percentage (percentage of carcass compared to live body weight). The model does not predict carcass percentage in the pig.

The model for grow-finish pigs also accounts for the effect of immunocastration in intact males, and effect of ractopamine supplementation in the diet on pig growth. Effect of immunization against GnRH in intact males is estimated with 21% increase in energy intake, 12% reduction in MMER, and 8% decrease in protein deposition. However, these effects were derived in the model from reverse modeling of response in energy intake because no empirical data were available when the model was developed (National Research Council 2012). Ractopamine supplementation to the pigs is estimated to increase the protein deposition in the pigs and influence of both the ractopamine level and duration of supplementation is considered in the model.

The grow-finish barn model also considers the amino acid content of the feed and influence of amino acids on weight gain in pigs. Protein deposition is also estimated using dietary levels of different amino acids available to the pigs and minimum of these estimated protein deposition values is then used for further calculations. Therefore, the model will predict lower average daily gains in pigs if the diet does not content enough amino acids.

Growth model for gestating and lactating sows or pregnant gilts principally works the same way as growth model for grow-finish pigs. The gestating sow model, in addition to maintenance energy, also considers energy required for standing and for thermogenesis. The protein pools in this model include protein depositions in conceptus, uterus, mammary glands and fetus. The protein deposition in the body of the sow is considered as a residual protein retention that cannot be attributed to the other pools. The daily feed intake of a pig is not calculated in the model. It is considered instead that the pigs are fed restricted diet and therefore, DFI is an input to the model. Effect of housing type (stalls or pens) and floor type (straws or other) in case of group housing is reflected in the lower critical temperature (LCT) of pig (Appendix B: National Research Council model for growth of gestating sows implemented in Pork Production Environmental Footprint (PPEF) model).

The lactating sow model considers the energy requirements for maintaining body functions and milk production of a sow when calculating protein and lipid deposition. The metabolizable energy in excess of the energy requirements for maintaining body functions and milk production is used for tissue growth. The litter size and expected average daily gain of piglets influences the weight gain or loss in the sow. Similar to model for grow-finish pigs, the DFI is calculated from MEI and metabolizable energy content of the feed (Appendix C: National Research Council model for growth of lactating sows implemented in Pork Production Environmental Footprint (PPEF) model)

SimaPro LCA model

The SimaPro software platform was used for comparing the mean values of each of the alternate management scenarios to the baseline or average production impacts and for analysis of the degree of confidence in the reported differences. The PPEF model output was used as input life cycle inventory and was imported to a life cycle analysis model developed in SimaPro V7.3 (Pre’ Consultants, The Netherlands). Environmental impacts associated with each member of the LCI were estimated using unit processes available in the Ecoinvent database in the SimaPro. This allows estimating and allocating upstream impacts associated with processes such as crop and fuel production to the total impact of pig production.

Chapter 3 Material and Methods

This study evaluated impacts of possible changes made to pork management practices on three impact categories: greenhouse gas emissions (GHG), fossil fuel use, and water use. All the test scenarios in this study were compared with a common baseline management scenario defined to represent current industry standards in pork production. Each test scenario evaluated only one management practice, where one key element was different from the baseline scenario. All the necessary inputs to the Pig Environmental Footprint (PPEF) model were manipulated to achieve expected changes in pig growth.

Sensitivity to temperature

The National Research Council's (NRC) growth model for wean-to-feeder pigs capture the effect of temperature by reducing metabolizable energy intake of pigs at temperatures greater than or equal to critical temperature plus three degree Celsius. During the alpha testing, the National Research Council's (NRC) growth model for grow-finish pigs was found to be sensitive to the temperature. This agreed with the experimental results where hot temperatures negatively impacted feed intake in pigs and heavier pigs were more sensitive to the warmer temperatures (Quiniou et al. 2000). To evaluate temperature sensitivity of NRC model, temperature anomaly was introduced in the model simulated for barrows. During three different simulations temperature in the barn was raised from 20^{o}C to 30^{o}C for ten days towards the beginning, midway, and towards the end of the growth cycle. All other inputs to the model were held constant. Changes in growth parameters of pigs were compared with model results obtained by simulating pig growth at 20^{o}C.

To examine effects of temperature sensitivity of model on GHG emissions, energy use and water use, the baseline scenario and all test scenarios were simulated by holding temperature constant at 20^{o}C (SCN01) and 25^{o}C (SCN02) for Wright County, Iowa, and by using temperatures from typical meteorological year for three locations in the United States: Wright County, Iowa (SCN03), Texas County, Oklahoma (SCN04), and Wake County, North Carolina (SCN05), representing three climatic regions in the United States. For SCN01 and SCN02 temperatures for NRC growth models were held constant at 20^{o}C and 25^{o}C respectively, while typical meteorological year for Wright County, Iowa was used for controlling fans, cooling pads, sprinklers, and heating pads.

Diet formulation and water consumption

Diet for all management scenarios was formulated using a scan level feed summary datasheet provided by swine nutrition specialist at the University of Arkansas (Table 3.1 and Table 3.2). Diet requirements and performance of pigs vary during their growth period in nursery, grow-finish, gestating and lactating phases. To capture these differences in diet, nursery (wean to feeder) and grow-finish (feeder to market) and sow barns were modeled individually. The grow-finish barn was divided in five phases as per the recommendations from swine nutrition specialist at the University of Arkansas. Separate diets were also formulated for gestating and lactating sows. Diet in nursery and sow barns and in each phase in the grow-finish barn represented typical diet composition in common management practice in the US. The last dietary phase in grow-finish barn was formulated to accommodate use of ractopamine by adding 0.05% Paylean 9 (Rikard-Bell et al. 2009; See et al. 2004). It was assumed that pigs have ad libitum access to the water and drinking water consumption, along with cooling and wash water, were simulated in the PPEF model.

Table 3.1- Diet formulation (% of dry feed) used for LCA of alternate management practices in the US for nursery and grow-finish barns

	Nursery	Grow barn base case				
		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Day at entering	**1**	**1**	**23**	**45**	**67**	**87**
Day at leaving	**42**	**22**	**44**	**66**	**86**	**End**
Copper sulfate, 25.2% Cu	0.07	0.10	0.10	0.00	0.00	0.00
Corn DDGs, high protein	13.16	20.00	20.00	20.00	20.00	0.00
Corn grain	46.55	56.41	61.91	66.21	68.78	76.75
DL-methionine	0.10	0.00	0.00	0.00	0.00	0.04
Fat	2.50	0.00	0.00	0.00	0.00	0.00
Fish meal	1.14	0.00	0.00	0.00	0.00	0.00
Lactose	0.26	0.00	0.00	0.00	0.00	0.00
Limestone, ground	0.84	0.97	0.98	0.95	0.90	0.63
L-lysine HCL	0.35	0.35	0.31	0.28	0.26	0.28
L-threonine	0.06	0.02	0.00	0.00	0.00	0.12
Monocalcium phosphate	0.73	0.65	0.60	0.51	0.50	0.85
Trace mineral premix (NB-8534)	0.15	0.15	0.15	0.15	0.13	0.15
Paylean 9g	0.00	0.00	0.00	0.00	0.00	0.03
Plasma spray-dried	0.59	0.00	0.00	0.00	0.00	0.00
Salt	0.45	0.60	0.50	0.50	0.50	0.50
Soybean meal, 47.5% CP	27.22	20.60	15.30	11.25	8.85	20.50
Vitamin premix (NB-6508)	0.25	0.15	0.15	0.15	0.10	0.15
Vitamin E (20000)	1.00	0.00	0.00	0.00	0.00	0.00
Whey, dried	4.49	0.00	0.00	0.00	0.00	0.00
Zinc oxide 72% Zn	0.09	0.00	0.00	0.00	0.00	0.00
Total %	100.00	100.00	100.00	100.00	100.00	100.00

Table 3.2- Diet formulation (% of dry feed) used for LCA of alternate management practices in the US for sow barn

	Gestation	Lactation
Corn ddgs, high protein	40.00	20.00
Corn grain	53.13	61.02
Fat	0.00	1.78
Limestone, ground	1.46	1.45
L-lysine HCL	0.20	0.25
L-tryptophan	0.00	0.00
Monocalcium phosphate	0.00	0.00
Sow add pack (NB-6442)	0.25	0.25
Trace mineral premix (NB-8534)	0.15	0.15
Phyzyme 1200	0.02	0.03
Ronozyme CT (10000)	0.02	0.02
Salt	0.45	0.50
Soybean meal, 47.5% CP	3.94	14.30
Vitamin premix (NB-6508)	0.25	0.25
Vitamin E (20000)	0.13	0.00
Total %	100.00	100.00

Barn type and infrastructure

A tunnel-ventilated house with deep-pit manure system and outside lagoon was used for the facility simulations. Cooling cells with water sprinklers, along with tunnel ventilation, were included for maintaining desired temperature inside the building. The PPEF model uses a typical meteorological year for a given location and estimates cooling, heating, or ventilation required to maintain thermo-neutral environment for pigs inside the barn. For weaned pigs 0.23 and 0.7 m^2 of floor space per pig (Hostetler et al. pers comm October 2012) was used in the nursery and grow-finish phases respectively. Additional floor space of 0.05 and 0.19 m^2 per pig was allotted for aisles and ancillary rooms in nursery and grow-finish barns respectively.

In gestation barn, changing housing the management practice from individual stalls to group housing (pens) required increase in the area from approximately 2 m^2 to 3.3 m^2 per animal. This results in additional barns to be constructed, and there can be significant environmental impacts associated with production and installations of the barn materials. To include impacts associated with barn construction and installations estimates for bills of material for nursery, grow-finish, and gestation barns were used in the analysis (Table 3.3). This is not an exhaustive accounting of all the material and the unit process modeled does no account for disposal of construction waste, nor for potential sediment runoff or other possible direct impacts associated with the barn construction. The figures in Table 3.3 provide a comparison of the impact profile associated with gestation pen housing and gestation stall housing.

Table 3.3- Bill of materials (major components) for barns used in simulations

Material	Units	Grow Barn (slatted floor)	Nursery Barn (mesh floor)	Gestation (pens, slatted floor)	Gestation (stalls, slatted floor)
		240 head	**160 head**	**120 head**	**120 head**
Aluminum roofing/siding	kg	754	382	1410	892
Concrete	m^3	64.6	16.3	130	80.2
Concrete block	kg	998	0	2990	1800
Copper (Wiring)	kg	3.1	3.1	3.1	3.1
Excavation	m^3	211	65.2	471	287
Foam Insulation	kg	899	522	1810	1150
Framing lumber	kg	2970	2060	3370	3060
Gestation Pen	p	#N/A	#N/A	12	#N/A
Gestation Stall	p	#N/A	#N/A	#N/A	120
Grow Barn Pen	p	12	#N/A	#N/A	#N/A
Nails	kg	40.6	25.3	58	44.4
Plastic sheeting	sq.ft	3970	2300	8000	5070
Plywood	kg	832	554	1450	978
Reinforcing steel	kg	760	366	1430	900
Sand	kg	16900	8700	37700	23000
Sanitary ceramics	kg	120	120	120	120
Transport (all materials)	tkm	46500	46500	93700	58100
Land	m^2	208	107	464	282

Baseline scenario

A single baseline scenario chosen to represent common management practices in the US was defined for the study (Table 3.4). Scenarios without RAC, antimicrobials, gestation stalls, inclusion of immunocastration, and production of intact males (boars) were compared pairwise with this baseline scenario. The baseline scenario included 500 pigs in both wean-to-feeder (nursery) and feeder-to-finish (grow-finish) barns. Both male and female pigs were included in equal numbers and the baseline scenario assumed growth promoting antimicrobial (AGP) use in the nursery, preventive antimicrobial use as required, ractopamine use in grow-finish barn, and tail docking and surgical castration of male pigs performed in the lactation barn. Multiplication factors of 0.87 and 0.8 for nursery and grow-finish barns respectively were used to adjust maintenance metabolizable energy requirement (MMER) of pigs in nursery and grow-finish barns in the PPEF model at a barn temperature of 20^{o}C to achieve 42 days in the wean-to-feeder phase and 114 days in feeder-to-finish phase as per the recommendations by National Pork Board Task Force. These multiplication factors were later used in all other scenarios for respective growth phases.

The NRC growth model for growing pigs assumes that the maximum protein deposition value (Pdmax) in pig decreases after a certain weight is reached (National Research Council 2012). The Pdmax values of 133, 137 and, 151 g day^{-1} were used for barrows, gilts, and entire males respectively and weight after which Pdmax in pigs start to decline was set to 90 kg. Paylean-9 was added to the diet in the last phase of feed formulation and at a pig body weight of 96 kg to simulate 28 days on the ractopamine. The average market weight of 125 kg (approx. 275 lbs) (National Pork Board ; USDA ; USEPA) was chosen for fair study. Mortality rate of 2.9 and 3.9% was used in wean-to-feeder and feeder-to-finish barns respectively.

Sow barn in the baseline scenario was a continuous operation and housed 1500 animals at any time in individual gestation crates. It was assumed that 825 gilts were added to the barn and 750 sows were culled each year. Litter size for baseline scenario was set to 10.5 piglets per year with 8.08 piglets surviving to weaning (Table 3.5). Days between farrowing and insemination were set to 16 (Table 3.6) to capture data published by Bates et al. (2003), who reported that 68.4% of sows housed in gestation stalls returned to estrus within 7 days after farrowing and 89.4% of those sows remained pregnant after the first insemination.

Table 3.4- Baseline scenario used for simulation

	Units	Wean-to-feeder	Feeder-to-finish
Age when pigs enter the barn	Days	21	
Weight when pigs enter barn	kg	5	23
Weight when pigs leave barn	kg	23	125
No of pigs entering barn each cycle		500	500
Mortality rate		2.9%	3.9%
Floor space per pig	m^2	0.23	0.696
Heating and cooling system		Tunnel Ventilation	Tunnel Ventilation
Heating Fuel		Natural Gas	Natural Gas
Maximum total throughput of all fans	cfm	282000	282000
Manure system		Deep Pit w/ lagoon	Deep Pit w/ lagoon

Table 3.5- Baseline scenario for sow barn

Parameter	Units	Sow Barn
Sows and gilts		
No of adult pigs kept in barn	Animals	1500
No of gilts added per year	Animals	825
Average age of gilts added	Days	180
No of days elapsed between gilt deliveries	Days	7
No. of sows culled per year	Animals	750
No. of days elapsed between culling of sows	Days	7
Piglets		
No. of piglets per litter surviving to weaning	Animals	8.08
No. of pigs dying per litter before weaning	Animals	2.42
Age at which piglets are removed from barn	Days	21
No. of days between piglet removal and insemination	Days	16
Piglet birth weight	Kg	1.5
Housing		
Barn area	m^2	3073
Barn type		Tunnel ventilation
Upper limit for temperature	ºC	27
Lower limit for temperature	ºC	16
Type of heating fuel	-	Natural gas
Piglet heaters system	-	Heating pads
Cooling system	-	Cooling cells with water sprinkler
Outside temperature to start cooling cells	ºC	22
Outside temperature to start sprinklers	ºC	24
Manure system	-	Deep pit with lagoon

Table 3.6- Example calculation for post-weaning time to the successful insemination for baseline scenario

Estrus/ Insemination Stalls				
Number of Animals	**Days after weaning**	**Fraction coming to estrus**	**Fraction remaining pregnant**	**Number pregnant of original 1000**
1000	7	0.684	0.894	611
389	28	1	0.894	347
42	49	1	0.894	37
5	70	1	0.894	4
Weighted Average:	16.1			

Removal of ractopamine (RAC)

Ractopamine is a dietary supplement which improves average daily gain (ADG) and feed efficiency (FE) in finishing pigs (Armstrong et al. 2004; Barbosa et al. 2012; Dunshea et al. 1993; Hinson et al. 2011) and is usually added to the diet during last 28 days in the finishing phase (Hostetler et al. 2012). Without RAC, reduced ADG and FE is observed in the pigs, which results in slower growth and higher daily feed consumption (Armstrong et al. 2004; Barbosa et al. 2012; Hinson et al. 2011; Lanferdini et al. 2013; Patience et al. 2009; Rikard-Bell et al. 2009). To simulate the effects of removal of RAC, Paylean-9 was removed from the last phase in the grow-finish barn (Table 3.7). The diet was also altered to accommodate more corn as per the recommendations from swine nutritionists at the University of Arkansas. A Boolean variable used for RAC in the PPEF model was turned ‘False’ to simulate exclusion of RAC in the grow-finish barn. No changes were made to the nursery and sow barn scenarios.

Table 3.7- Diet formulation (% of dry feed) used for removal of RAC scenario

	Nursery	**Grow barn**				
		Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**
Day at entering	**1**	**1**	**23**	**45**	**67**	**87**
Day at leaving	**42**	**22**	**44**	**66**	**86**	**End**
Copper sulfate, 25.2% Cu	0.07	0.10	0.10	0.00	0.00	0.00
Corn DDGs, high protein	13.16	20.00	20.00	20.00	20.00	0.00
Corn grain	46.55	56.41	61.91	66.21	68.78	86.08
DL-methionine	0.10	0.00	0.00	0.00	0.00	0.00
Fat	2.50	0.00	0.00	0.00	0.00	0.00
Fish meal	1.14	0.00	0.00	0.00	0.00	0.00
Lactose	0.26	0.00	0.00	0.00	0.00	0.00
Limestone, ground	0.84	0.97	0.98	0.95	0.90	0.65
L-lysine HCL	0.35	0.35	0.31	0.28	0.26	0.20
L-threonine	0.06	0.02	0.00	0.00	0.00	0.04
Monocalcium phosphate	0.73	0.65	0.60	0.51	0.50	0.90
Trace mineral premix (NB-8534)	0.15	0.15	0.15	0.15	0.13	0.13
Paylean 9g	0.00	0.00	0.00	0.00	0.00	0.00
Plasma spray-dried	0.59	0.00	0.00	0.00	0.00	0.00
Salt	0.45	0.60	0.50	0.50	0.50	0.50
Soybean meal, 47.5% CP	27.22	20.60	15.30	11.25	8.85	11.40
Vitamin premix (NB-6508)	0.25	0.15	0.15	0.15	0.10	0.10
Vitamin E (20000)	1.00	0.00	0.00	0.00	0.00	0.00
Whey, dried	4.49	0.00	0.00	0.00	0.00	0.00
Zinc oxide 72% Zn	0.09	0.00	0.00	0.00	0.00	0.00
Total %	100.00	100.00	100.00	100.00	100.00	100.00

Antimicrobial use

Antimicrobials are used in animal industry for disease prevention, animal health improvement (Romina Ross et al. 2010), and as growth stimulants (Kiarie et al. 2011). However, antimicrobial use in animal industry has come under scrutiny due to the concerns about development of antimicrobial resistant strains that could affect human health (Holt et al. 2011). We constructed scenarios to evaluate the impacts associated with reduced use of antimicrobials in pig production. The first scenario assessed impact of eliminating growth promoting antimicrobials (AGP), while the second scenario assessed impacts of eliminating both growth promoting and preventive antimicrobial (NoPrev) use from the production. While impact of reducing or eliminating AGP or growth preventive antimicrobial use in the production could vary for high, median, and low health facilities, it was estimated that about 70% of the pigs reared in the US are in median health facilities and remaining 10 and 20% of the pigs are in low and high health facilities respectively (NPB Task Force, 2012). Considering these estimates, LCA analysis was carried out for median health status facilities only.

No Growth Promoting Antimicrobial Use

Williams et al. (1997) estimated that MMER of pigs in the body weight range of 6 and 27 kg would increase from 102 kcal kg^{-1} $BW^{0.75}$ to 115 kcal kg^{-1} $BW^{0.75}$ for pigs with high and low health status respectively. This was an estimated 12.7% increase in the MMER when pigs have poor health. To simulate elimination of AGP from the production in the nursery phase, the MMER of pigs for body weight between 5 and 23 kg was increased by 12.7%. This increase in the maintenance energy was on top of the multiplication factors used in the MMER formula. The grow-finish phase of the production was assumed to be unaffected by elimination of AGP, as far as pig performance is concerned.

Not using AGP could mean fewer pigs would reach the expected weight and size requirements in the production facility, which was estimated to increase voluntary cull rate in the nursery and grow-finish barn to 0.25% for median health facilities (NPB Task force, 2012, unpublished). Without AGP, the mortality rate was expected to increase by 0.2% in the nursery phase. Because AGP is used mostly in the nursery phase, production without use of AGP was expected to have no impact on mortality rates in grow-finish barn. No change due to elimination of AGP was anticipated on other performance factors such as diet formulation or average vet visits.

No Preventative Antimicrobial Use

In this scenario, the effects of production without use of either AGP or preventive antimicrobial use on performance parameters were estimated. When herd health is trending downward, antimicrobials are used prophylactically to reduce the chance of herd-wide infection. Animals which become sick are treated therapeutically and will recover or die. Without preventive use, more animals are likely to need therapeutic doses. Whittemore et al. (2001) reported that chronic diseases in pigs increase the maintenance energy requirements by up to 1.3 times the normal predicted value. However, in the current scenario it was assumed that not using preventive antimicrobials in the grow-finish barn does not necessarily mean the pigs fall sick. It was assumed that without AGP and preventive antimicrobials in the production, the performance of pigs would be poor compared to the baseline. Therefore, MMER of pigs in the nursery and grow-finish barns was increased by 12.7% (Williams et al. 1997) and 15% respectively. These changes to the MMER were combined the multiplication factors derived in the baseline scenario to match the number of days to the market weight. Without AGP and preventive antimicrobial use in the production the voluntary cull rates and mortality was expected to increase by 4% in the nursery and 5 and 5.5% respectively in grow-finish barn.

Surgical castration versus immunocastration and entire males (boars)

Surgical castration of male pigs without anesthesia within first 1 to 2 weeks of age is a standard industry practice (FAO ; Thun et al. 2006). Besides preventing boar taint in the meat, which is a result of skatole levels higher than 0.2 μg g^{-1} of fat, surgical castration also improves meat quality and suppresses aggressive behavior in pigs (Dunshea et al. 2001; Morales et al. 2010; Thun et al. 2006). However, surgical castration is under scrutiny of animal welfare groups because the procedure inflicts pain and distress in pigs (Millet et al. 2011; Morales et al. 2010).

An alternative to the surgical castration that is being studied is immunocastration. Immunocastration involves administering male pigs a dose of gonadotropin-releasing hormone (GnRH) which creates antibodies against GnRH and reduce skatole production. Dunshea et al. (2001) reported that immunocastration also reduces size of testes in male pigs suppressing sexual aggressive behavior. An analog of this compound is developed by Pfizer Pharmaceuticals Inc., which is marketed as Improvac® (also called Improvest®). Pfizer Animal Health recommends administering this compound at about 9 weeks of age and then again at least 4 weeks after the primary dose and schedule the slaughter between third and tenth week following the second dose to avoid boar taint.

Because male pigs behave more like boars until the second dose of GnRH compound, immunocastration offers improved ADG and FE in male pigs compared to surgically castrated pigs (Batorek et al. 2012b). After second vaccination however, immunocastrated pigs behave more like barrows.

For evaluation of environmental impacts of these changes in performance of immunocastrated (IC) pigs, a split sex barn was assumed to rear entire males and gilts. The NRC growth model for growing-finishing pigs assumes not effect of pig sex on the MMER (National Research Council 2012). However, it is assumed in the model that entire males have lower metabolizable energy intake (MEI) compared to the barrows. The MEI of entire males was calculated using Eq. 3.1.

$$\mathrm{MEI} = 10638.34678 \times (1 - \exp(-\exp(-3.803287531) \times \mathrm{BW}^{0.907224509})) \qquad \text{Eq. 3.1}$$

Where, MEI = metabolizable energy intake, kcal day^{-1}

BW = body weight of a pig, kg

Until the second dose of GnRH compound is administered, the male pigs behave more like boars, which means they gain leaner muscle mass. To simulate higher protein deposition in the male pigs, the Pdmax value of 151 g day^{-1} was used for immunocastration scenario. This Pdmax value was higher compared to both barrows (133 g day^{-1}) and gilts (137 g day^{-1}). It was considered that the second vaccination was administered at a body weight of 88 kg (Fabrega et al. 2010). This body weight was used to trigger part of the algorithm that simulates effects of immunocastration on uncastrated male pigs. Effects of immunocastration on boars were captured in the model by increasing estimated MEI by 21% and reducing MMER and Pd by 12 and 8% respectively. At body weight of 96 kg IC pigs were supplemented with 10 mg RAC per kg of feed by adding 0.05% of Paylean-9 in the diet. No changes to the diet formulation were made for the immunocastration scenario. Carcass yield of 75.35% obtained from the averaging the data reported in the peer-reviewed articles (Andersson et al. 2012; Batorek et al. 2012b; Dunshea et al. 2011; Dunshea et al. 2001; Font-i-Furnols et al. 2012; Morales et al. 2010; Pauly et al. 2009;

Skrlep et al. 2010a; Skrlep et al. 2010a; Skrlep et al. 2010b; Zamaratskaia et al. 2008) was used in this scenario.

For entire male (EM) scenario, inputs similar to the IC scenario, except for the dose of GnRH inhibitors and use of RAC were used. It was assumed that for both boars and IC barrows, their performance in the wean-to-feeder phase would be similar. For the entire male scenario, two separate barns each containing 250 entire males and gilts were simulated. Based on expert opinion (Bill Close, pers. comm.), market weight of entire males was set to 91 kg (approx. 200 lb) while the market weight of gilts was set to 125 kg. Average of carcass yields reported by Andersson et al. (2012); Batorek et al. (2012b); Dunshea et al. (2011); Morales et al. (2010); Pauly et al. (2009); Skrlep et al. (2012); Skrlep et al. (2010b); Zamaratskaia et al. (2008) were used for carcass yield in the EM scenario.

Gestation stalls

While gestation stalls used in the sow barn offer benefits such as maximum barn space utilization and controlled feeding, the management practice has drawn some protest from animal welfare groups because the stalls offer sow minimum or no free movement (Lammers et al. 2007). However, group housing poses its own problems. Sows housed in group are more prone to injuries resulting in stress and injury; however we found no quantitative data to enable inclusion of these effects in the modeled animal productivity. There is a trade-off between protecting animals from injuries and providing freedom of movement. Also, group housing reduces the stocking density and thus requires additional housing to maintain animal production. Due to the difference in barn infrastructure necessary for the alternate management using gestation pens, the LCA scenarios have included the effect of changes in the infrastructure. A 10 year life for the barn facility, including the stalls and pens was assumed for this scenario. A bill of materials for construction of sow, nursery and grow-finish barns from plans published by Iowa State University Midwest Plan Service (Iowa State University, 2012) was created (Table 3.3).

This scenario was designed to evaluate environmental impact of production management using gestation pens. Data for comparison between gestation stalls and group pen housing were obtained from published articles. This scenario evaluated the option of using gestation stalls for the entire gestation period only. It was assumed that farrowing stalls were used for both group pen and individual stall scenarios. The differences between sows housed in gestation stalls and in group pens were observed in number of live births, litter size, pre-weaning mortality, and piglet weights at birth. An analysis of data obtained from peer-reviewed articles (Anil et al. 2005; Bates et al. 2003; Harris et al. 2006; Jansen et al. 2007; Lammers et al. 2007; McGlone et al. 2004; SCHMIDT et al. 1985; Weng et al. 2009) was performed to prepare scenarios for group and gestation housing (Table 3.8). Backfat thickness of 19.6 and 20 mm (Salak-Johnson et al. 2007) and pre-weaning mortality of 14 and 15% (Lammers et al. 2007) were used for stalls and group pens respectively.

Bates et al. (2003) reported that 72% of sows housed in group returned to estrus within 7 days compared to 68.4% of sows in gestation stalls. In addition, 94.3% of group housed sows remained pregnant after initial service compared to 89.4% of sows in stalls. These differences were capture in the PPEF model by adjusting the number of average number of days between piglet removal and insemination. An example calculation to estimate the herd average time between weaning and successful insemination is presented in Table 3.9.

Table 3.8- Production parameters for gestation stalls and group housing (pens)

Parameters	Units	Sow Barn, stalls	Sow Barn, pens
Sows and gilts			
No of adult pigs kept in barn		1500	1500
No of gilts added per year		825	825
Average age of gilts added		180	180
No of days elapsed between gilt deliveries		7	7
No. of sows culled per year		750	750
No. of days elapsed between culling of sows		7	7
Piglets			
No. of piglets per litter surviving to weaning		8.08	7.88
No. of pigs dying per litter before weaning		2.42	2.47
Age at which piglets are removed from barn		21	21
No. of days between piglet removal and insemination		16	14
Piglet birth weight	kg	1.5	1.53
Housing			
Barn area	m^2	3073	3073
Barn type		Tunnel ventilation	Tunnel ventilation
Upper limit for temperature	^oC	27	27
Lower limit for temperature	^oC	16	16
Heating fuel		Natural gas	Natural gas
Piglet heaters		Heating pads	Heating pads
Cooling system		Cooling cells with water sprinkler	Cooling cells with water sprinkler
Outside temperature to start cooling cells	^oC	22	22
Outside temperature to start sprinklers	^oC	24	24
Manure system		Deep pit with lagoon	Deep pit with lagoon

Table 3.9- Example calculation for comparison of gestation stalls and group housing: post-weaning time to the successful insemination

Estrus/ Insemination Group Pens				
Number of Animals	**Days after weaning**	**Fraction coming to estrus**	**Fraction remaining pregnant**	**Number pregnant of original 1000**
1000	7	0.72	0.934	672
328	28	1	0.934	306
22	49	1	0.934	20
Weighted Average:	14.3			

Uncertainty Analysis

An uncertainty analysis for baseline and each of the treatments in the comparative study was performed using Monte Carlo analyses to gain a confidence in the results obtained in the study. Assuming that ADG, DFI, FE, water consumption, and mortality values in the comparative study represent the mid values, two more scenarios for each test scenario including baseline were prepared. The parameters in the model were adjusted to obtain minimum and maximum carbon footprint for baseline and corresponding test scenarios. In PPEF model, the MMER was adjusted to create the scenarios yielding minimum and maximum carbon footprint. For a given body weight, MMER of a pig could vary between $191\times BW^{0.6}$ kcal to $215\times BW^{0.6}$ kcal, with an average of $197\times BW^{0.6}$ (National Research Council 2012). This gives a range of MMER values, which could be 3% lower or 9.65% higher compared to the mean value of used for the comparative analysis. Lowering MMER would mean less energy required for body maintenance and more energy left for the weight gain. This will yield a scenario with minimum carbon footprint. Increasing the MMER would mean less energy will be available for weight gain which will yield the scenario with maximum carbon footprint. Therefore, a multiplication factors of 3 and 9.65% were used in each of the scenarios for preparing LCI with minimum and maximum carbon footprint respectively for respective scenarios. These changes to the MMER were made in addition to any multiplication factors used in the comparative analysis.

National Pork Board Antibiotic Resistance Taskforce Report provided percentage change in mortality if antimicrobials were not used in the swine production. This change to mortality rate was 0.2% for production without growth promoting antimicrobial use for both nursery and grow-finish barns. The task force expected only 50% of the reported impact on mortality if Carbadox are still used in the production. For the baseline, no ractopamine, immunocastration, entire males, and gestation pens scenarios use of Carbadox was assumed in the production and change in the mortality was assumed to be 25% of the reported change without GP antimicrobial use in median health production. Changes to the mortality rate and voluntary cull rate for production without antimicrobials scenarios are tabulated in Table 3.10. For sow barn the scenarios yielding maximum and minimum carbon footprint were prepared using the maximum and minimum numbers for preweaning mortality, pigs born alive, and litter birth weight (Table 3.11)

The SCN01 and SCN02 scenarios were simulated by fixing the temperature in NRC growth model to 20^{o}C and 25^{o}C. These scenarios were strictly used to estimate the effect of temperature on the model results and did not represent reality. Therefore, SCN01 and SCN02 were excluded from uncertainty analysis.

Table 3.10- Changes made to mortality rate and voluntary cull rate for uncertainty analysis of Antimicrobial use scenarios

Parameter	Units	Minimum impact	Maximum impact
No Growth promoting antimicrobials			
Change to mortality rate (nursery)	%	0	2
Change to mortality rate (grow-finish)	%	0	1
Change to voluntary cull rate (nursery)	%	0	2
Change to voluntary cull rate (grow-finish)	%	0	1
No preventative antimicrobials			
Change to mortality rate (nursery)	%	2	15
Change to mortality rate (grow-finish)	%	0	10
Change to voluntary cull rate (nursery)	%	2	6
Change to voluntary cull rate (grow-finish)	%	0	10

Mortality rate for uncertainty analysis was sum of respective mortality rates used for comparative analyses (2.9% for nursery; 3.9% for grow-finish) and changes to the mortality and voluntary cull rate

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Table 3.11- Sow barn parameters used for uncertainty analysis for gestation stalls and group housing

Parameter	Units	Minimum impact	Maximum impact
Gestation Stalls			
No. of piglets per litter surviving to weaning	Animals	9.09	7.31
No. of pigs dying per litter before weaning	Animals	1.91	3.59
Age at which piglets are removed from barn	Days	21	21
No. of days between piglet removal and insemination	Days	16	16
Piglet birth weight	kg	1.53	1.31
Gestation pens (group housing)			
No. of piglets per litter surviving to weaning	Animals	9.03	6.33
No. of pigs dying per litter before weaning	Animals	1.77	3.18
Age at which piglets are removed from barn	Days	21	21
No. of days between piglet removal and insemination	Days	14	14
Piglet birth weight	kg	1.64	1.48

Chapter 4 Results and discussion

In this study environmental impact of alternate management practices were evaluated by using five temperature regimes in Pig Environmental Footprint (PPEF) model. These temperature scenarios included

1. Fixing temperature in grow and sow growth sub-module at 20°C (SCN01); using geographical location: Wright County, Iowa
2. Fixing temperature in grow and sow growth sub-module at 25°C (SCN02); using geographical location: Wright County, Iowa
3. Using Typical Meteorological Year (TMY) for regulating temperature in the barn at Wright County, Iowa (SCN03)
4. Using TMY for regulating temperature in the barn at Texas County, Oklahoma (SCN04)
5. Using TMY for regulating temperature in the barn at Wake County, North Carolina (SCN05)

Temperature sensitivity of model

The systematic temperature anomaly introduced in the model clearly showed sensitivity of NRC model for grow-finish pigs to the temperature in the barn. This temperature sensitivity of the model was evident through increased number of days in the barn required to reach market weight (Figure 4.1). This reduced daily gain, which resulted in longer production cycles, was mainly a result of reduced metabolizable energy intake (MEI) observed at higher temperatures, which lowered the feed intake in pigs leaving less energy available for weight gain after maintenance requirements were satisfied. Days required to gain weight from 5 kg to 125 kg increased from 158 days at 20°C to 172 days when temperature was increased to 30°C after 148 days in to production. Effect of temperature on pig growth was more prominent for temperature anomalies introduced during the later phase of the growth cycles. These results were consistent with Quiniou et al. (2000) who observed negative impact of higher temperatures on voluntary feed intakes, in heavier pigs.

Temperature sensitivity of model was also evident through results of LCA simulations. For baseline scenario, estimated greenhouse gas emissions was lowest for SCN01 (3.298 kg CO_2e) and highest for SCN05 (3.984 kg CO_2e). Similar trends were also observed fossil fuel energy use and water use for baseline scenarios at different temperature regimes.

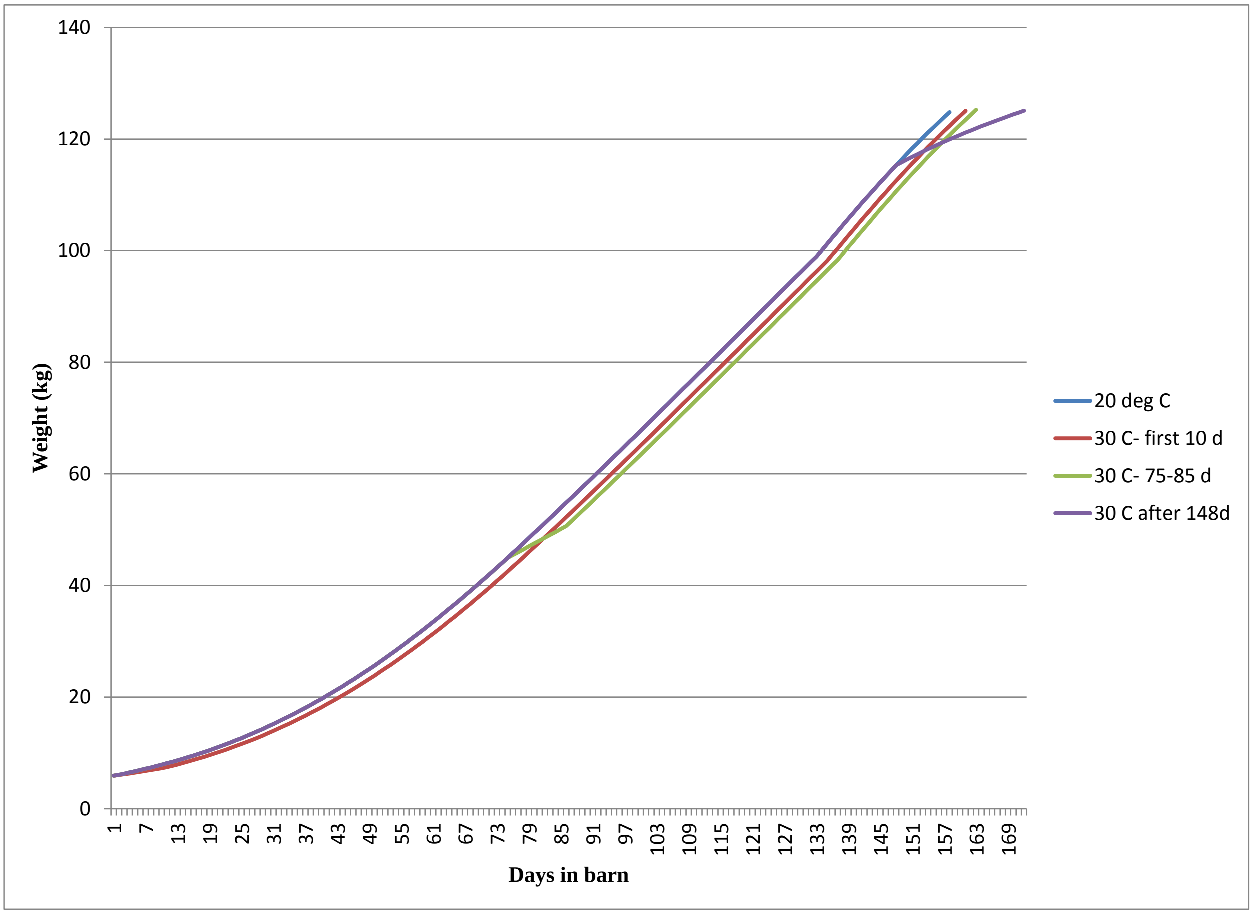

Figure 4.1- Effect of systematic temperature anomaly introduced in the model on growth of pigs

Comparative Life Cycle Assessment

Results of the LCA for the baseline and six pork production management strategies are presented in Table 4.1. The five temperature scenarios evaluated in this study are assessment of impacts of temperature on sustainability metrics. As seen in Figure 4.1 growth of pigs estimated by the NRC growth model is sensitive to the temperature. The five temperature scenarios are the surrogate of location impacts across the United States and an alternative management practice for a particular temperature scenario was compared with a respective baseline only. All the pork production management strategies were analyzed based on changes to the impact categories, which were a result of changes in unit processes, life cycle inventories, and/or days in the barn. Analysis of the changes in environmental impact category metrics for each pork production management strategy for one kilogram live pork at the farm gate showed that some strategies increased impacts, while others decreased impacts (Figure 4.2, Figure 4.3, and Figure 4.4). The analyses represent simulated estimates of impacts and should be interpreted as potential trends rather than absolute estimates.

Table 4.1- Environmental impact estimates for baseline and alternative US swine management practices, reported per kg live weight at the farm gate

Alternative management strategy	Impact Category	SCN01	SCN02	SCN03	SCN04	SCN05
Baseline	IPCC GWP 100a (kg CO_2e)	3.298	3.306	3.374	3.734	3.985
	Non-renewable (MJ)	21.510	21.430	21.989	22.126	22.001
	Water (m^3)	0.167	0.174	0.179	0.185	0.185
Entire Males	IPCC GWP 100a (kg CO_2e)	3.304	3.377	3.444	3.731	4.046
	Non-renewable (MJ)	21.916	22.231	22.814	22.507	22.610
	Water (m^3)	0.160	0.170	0.175	0.177	0.181
Gestation Pens	IPCC GWP 100a (kg CO_2e)	3.268	3.274	3.341	3.701	3.954
	Non-renewable (MJ)	21.165	21.106	21.660	21.789	21.663
	Water (m^3)	0.165	0.172	0.177	0.184	0.183
Immunocastration	IPCC GWP 100a (kg CO_2e)	3.185	3.252	3.293	3.671	3.942
	Non-renewable (MJ)	20.770	21.007	21.425	21.703	21.594
	Water (m^3)	0.160	0.169	0.174	0.180	0.182
No Groth Promoting	IPCC GWP 100a (kg CO_2e)	3.343	3.361	3.426	3.890	4.049
	Non-renewable (MJ)	21.832	21.814	22.373	23.080	22.424
	Water (m^3)	0.169	0.176	0.181	0.193	0.187
No Preventive	IPCC GWP 100a (kg CO_2e)	3.780	3.873	3.958	4.328	4.700
	Non-renewable (MJ)	24.814	25.240	26.035	25.884	26.027
	Water (m^3)	0.189	0.201	0.207	0.211	0.215
No Ractopamine	IPCC GWP 100a (kg CO_2e)	3.379	3.436	3.593	3.935	4.148
	Non-renewable (MJ)	21.809	22.039	23.060	22.963	22.295
	Water (m^3)	0.172	0.182	0.193	0.196	0.192

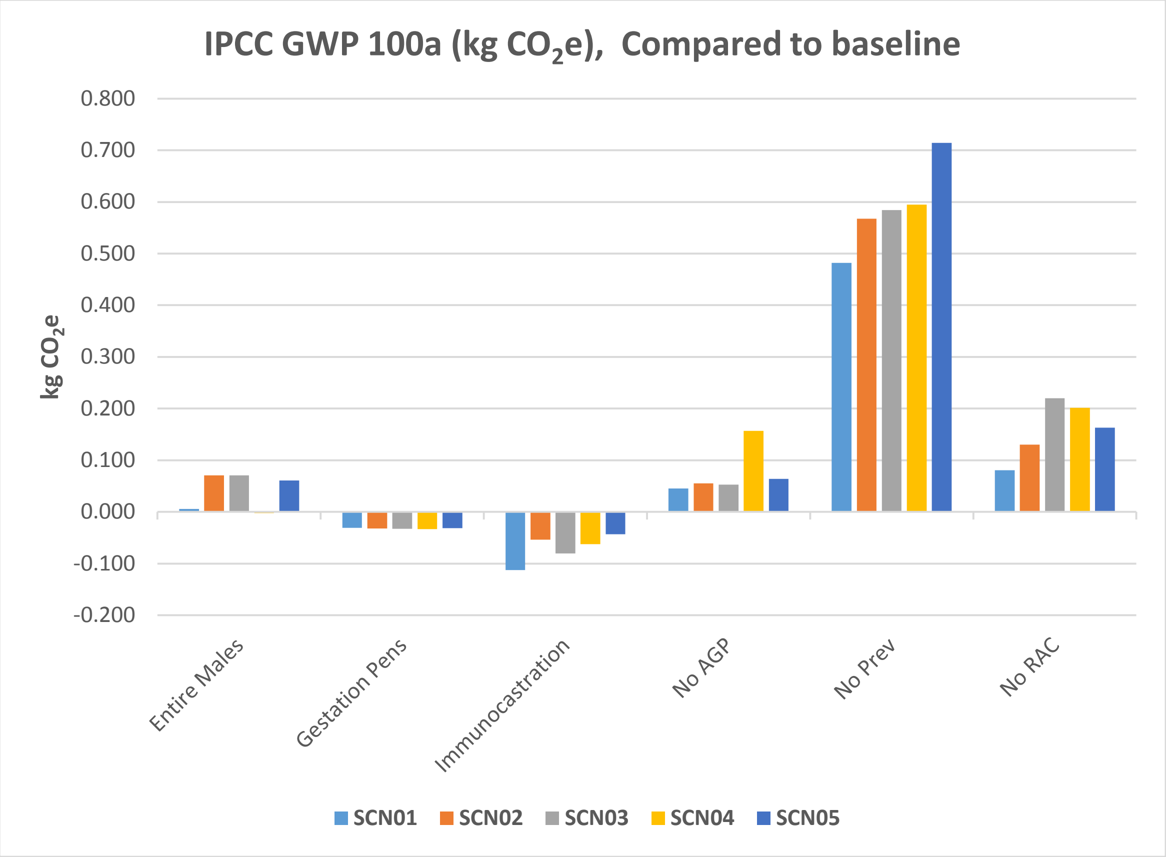

Figure 4.2- Changes to the greenhouse gas emissions for alternative US swine management practices, compared to the baseline, reported per kg live weight at the farm gate

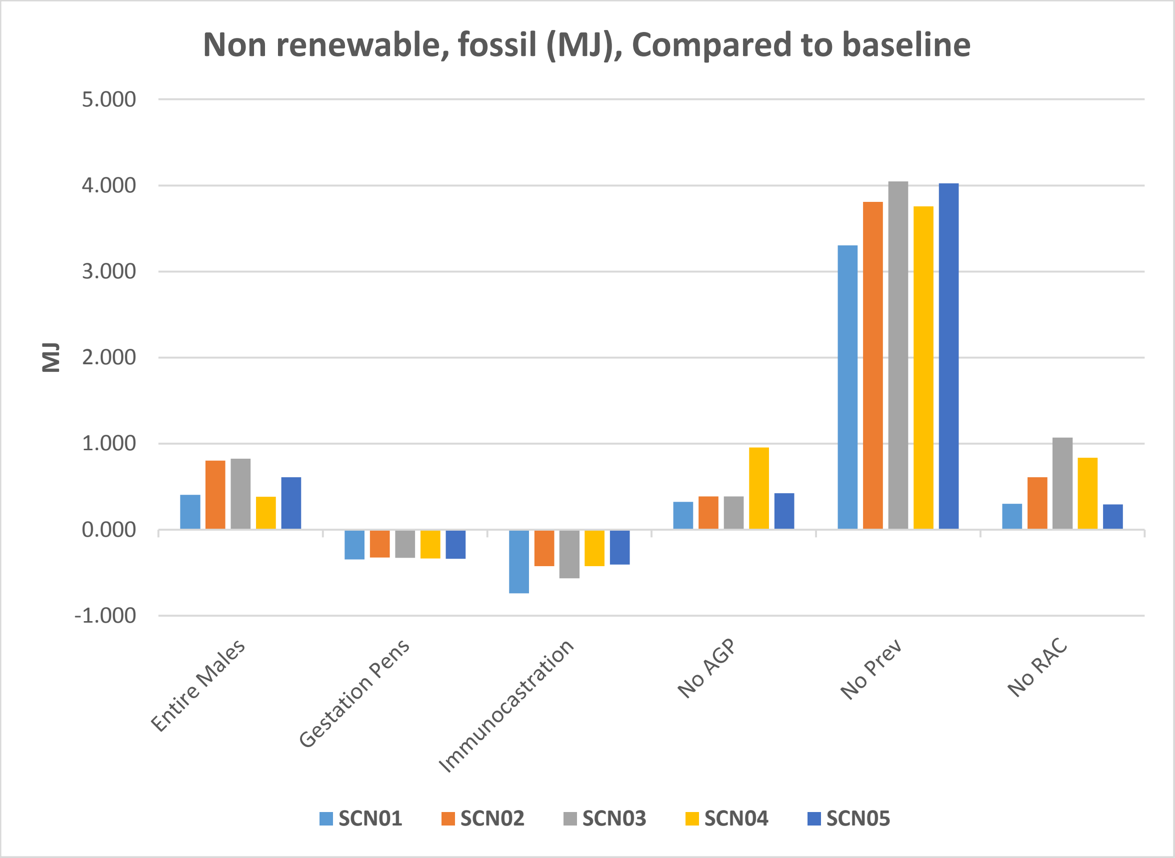

Figure 4.3- Changes to the non-renewable energy use for alternative US swine management practices, compared to the baseline, reported per kg live weight at the farm gate

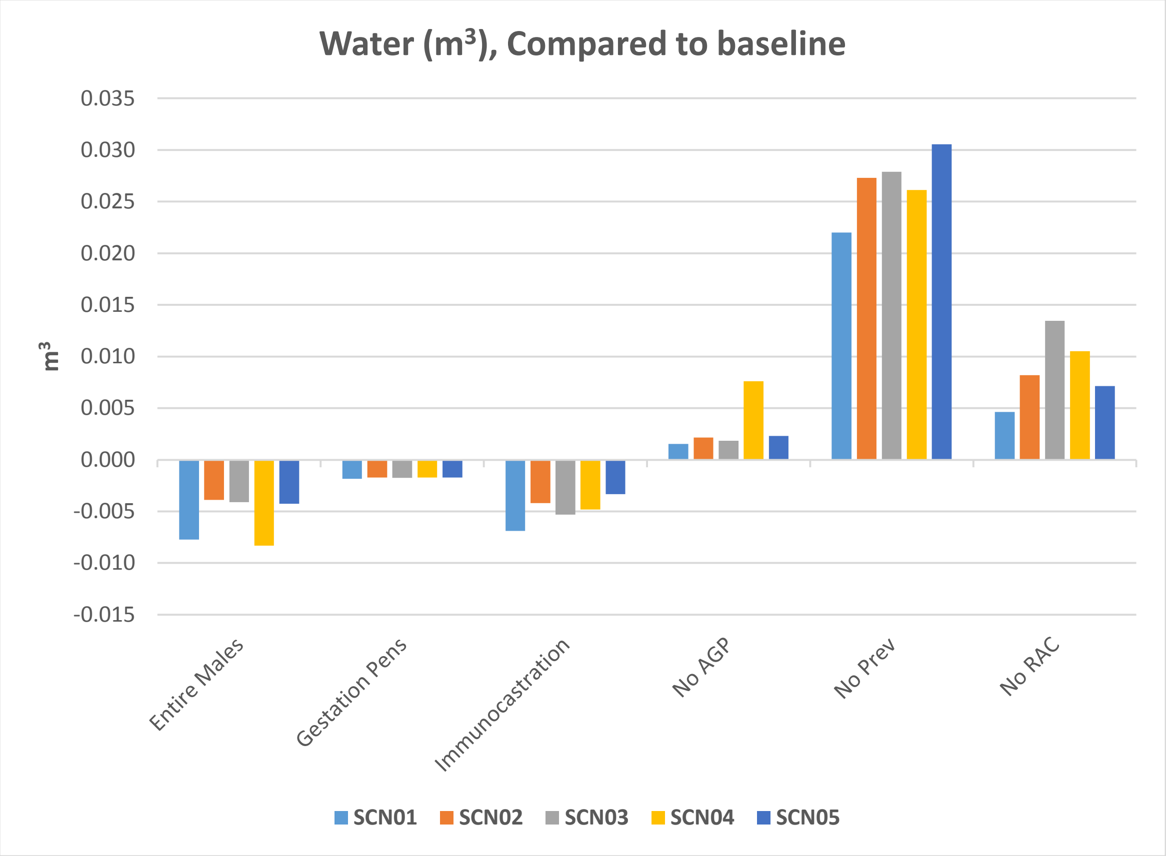

Figure 4.4- Changes to the water use for alternative US swine management practices, compared to the baseline, reported per kg live weight at the farm gate

Removal of Ractopamine

Not using ractopamine resulted in increase in GWP, energy use, and water use for all five temperature regimes. The driving factor for this increase in GWP from removal of ractopamine as a growth promoting agent was lowered productivity during last month of finishing. The model simulations showed that days in the barn required to reach market weight increased when RAC was not used in the production. This directly affects the quantity of feed consumed, manure produced, and requires a small increase in necessary barn infrastructure to support the same annual pork production (i.e., a decrease in the number of turn per barn per year).

Increase in sustainability metrics ranged from 2.4% increase in GWP, 1.3% increase in energy use, and 2.2% increase in water use for simulations at 20°C to 6.5% increase in GWP, 4.6% increase in energy use, and 5.6% increase in water use for simulations at Wright County, Iowa which used TMY for temperature predictions (Table 4.2).

Table 4.2- Percentage changes in impact category metrics for No Ractopamine scenario compared to the baseline reported per kg live weight at the farm gate

Alternative management strategy	Impact Category	SCN01	SCN02	SCN03	SCN04	SCN05
No Ractopamine	IPCC GWP 100a (kg CO_2e)	2.438	3.936	6.515	5.394	4.093
	Non-renewable (MJ)	1.387	2.842	4.867	3.783	1.337
	Water (m^3)	2.774	4.723	7.518	5.678	3.859

Antimicrobials

Two distinct scenarios were analyzed in this study which included production without AGP in the nursery barn and production without AGP and preventive antimicrobials throughout the growing period. For both NoAGP and NoPrev scenarios, increase in GWP, energy use, and water use were observed but production without AGP and preventive antimicrobials showed the highest impact amongst two.

No growth promoting antimicrobials

Not using antimicrobials as a growth promoting strategy resulted in increase in GWP, energy use, and water use that ranged from 1.4%, 1.6%, and 3.1% respectively for simulations at 20^{o}C to 4.2%, 4.3% and 6% respectively for simulations at Texas County, Oklahoma which used TMY for temperature predictions (Table 4.3). The increased GWP was driven by two factors: lowered daily gain and feed efficiency leading to increased feed consumption and time required to reach market weight, and therefore additional manure production as well. Finally, additional barn infrastructure will be needed due to lengthened time to reach market weight.

Table 4.3- Percentage changes in impact category metrics for No Growth Promoting Antimicrobials scenario compared to the baseline, reported per kg of live weight at the farm gate

Alternative management strategy	Impact Category	SCN01	SCN02	SCN03	SCN04	SCN05
No Growth Promoting	IPCC GWP 100a (kg CO_2e)	1.370	1.665	1.559	4.197	1.609
	Non-renewable (MJ)	1.494	1.793	1.746	4.311	1.925
	Water (m^3)	0.914	1.232	1.038	4.103	1.245

No growth promoting or preventive antimicrobials

Coupling removal of AGP with production without antimicrobials for disease prevention resulted in the highest impact across the sustainability metrics amongst all scenarios. Increase in GWP, energy use, and water ranged between 14.7%, 15.5%, and 16.4% for simulations at 20^{o}C to 17.4%, 18.6%, and 18.9% respectively for simulations at Wright County, Iowa with TMY used for temperature prediction (Table 4.4). The effects of not using antimicrobials for both growth promotion and disease prevention were driven by the same process impacts as not using AGP in the production, compounded by increased mortality, and reduced performance across the entire heard.

Table 4.4- Percentage changes in impact category metrics for No growth promoting or preventive antimicrobials scenario compared to the baseline, reported per kg of live weight at the farm gate

Alternative management strategy	Impact Category	SCN01	SCN02	SCN03	SCN04	SCN05
No Preventive	IPCC GWP 100a (kg CO_2e)	14.611	17.161	17.321	15.925	17.934
	Non-renewable (MJ)	15.358	17.782	18.399	16.985	18.298
	Water (m^3)	13.159	15.731	15.577	14.091	16.536

Immunocastration

This management alternative resulted in lower GWP, energy use and water use for five temperature regimes. Decrease in GWP, energy use, and water use for immunocastration scenario ranged between 3.4%, 3.4%, and 2.8% respectively for simulations at 20^{o}C and 1.3%, 1.9%, and 0.1% for Wake County, NC respectively (Table 4.5). This alternative approach to controlling boar taint resulted in increased average daily gain and reduced daily feed intake compared to the baseline. In the grow barn, using immunocastration technique also resulted in more number of cycles per year. This resulted in less overall feed consumption and manure production as well as a small reduction in necessary barn infrastructure associated with the faster average turn-around for the barns.

Table 4.5- Percentage changes in impact category metrics for immunocastration scenario compared to the baseline, reported per kg of live weight at the farm gate

Alternative management strategy	Impact Category	SCN01	SCN02	SCN03	SCN04	SCN05
Immunocastration	IPCC GWP 100a (kg CO_2e)	-3.422	-1.621	-2.385	-1.667	-1.088
	Non-renewable (MJ)	-3.444	-1.973	-2.567	-1.912	-1.850
	Water (m^3)	-4.124	-2.415	-2.963	-2.601	-1.796

Gestation pens

Using pen gestation structures rather than stall gestation structures resulted in decrease in GWP, energy use, and water use. Compared with baseline, decrease in GWP, energy use, and water use was 0.98%, 1.5%, and 0.3% respectively for Wright County, IA, which appeared to perform best (Table 4.6). The NRC growth model for gestating sow assumes lower impact of temperature on MMER for group housed sows, which reduces the maintenance energy requirements leaving more energy available for fetus development and weight gain. Therefore, lower GWP observed in this scenario was a result of better performance of sows, lower feed consumption, and lower manure emissions. However, the barn infrastructure requirements for pens are 65% larger, based on our modeling of the space requirements for sow in stalls compared to pens. This increases the GWP, which is amortized over the expected life of the barn (10 years), and essentially offsets the lower GWP observed for this scenario. The lower energy demand appears to be a result of lower electricity use for fans observed for gestation pens.

Table 4.6- Percentage changes in impact category metrics for gestation pens scenarios compared to the baseline, reported per kg of live weight at the farm gate

Alternative management strategy	Impact Category	SCN01	SCN02	SCN03	SCN04	SCN05
Gestation Pens	IPCC GWP 100a (kg CO_2e)	-0.930	-0.967	-0.973	-0.886	-0.782
	Non-renewable (MJ)	-1.604	-1.512	-1.499	-1.523	-1.537
	Water (m^3)	-1.108	-0.986	-0.972	-0.922	-0.923

Entire males

This scenario was evaluated by growing entire males to 91 kg and gilts to 125 kg. This alternate management practice resulted in marginally higher GHG emissions for SCN01, SCN02, SCN03 and SCN05 (0.176, 2.144, 2.092, and 1.531% respectively). For SCN04, where TMY was used for Texas County, OK, 0.0062% lower GHG emissions were observed (Table 4.7). While, entire males have an advantage of leaner body composition, this was not captured in the scenario because a functional unit of one kg live weight at the farm gate was used. Higher GHG emissions observed in most of the scenarios could be associated with more number of pigs required to reach annual live weight production demand, since average weight of pigs in this scenario would be 108 kg compared to 125 kg used for the baseline. Which means there will be increased feed consumption and manure excretion per year.

For all temperature regimes this alternate management practice resulted in higher energy use and lower water use (Table 4.7). Increase in energy use was 1.885, 3.738, 3.748, 1.719, and 2.767% for SCN01, SCN02, SCN03, SCN04, and SCN05 respectively. This increased fossil fuel consumption appears to be associated with the relatively larger (i.e. per kg live weight) amount of energy needed for maintaining temperatures at a suitable level in the barn for smaller animals.

Smaller animals do not generate as much body heat and will, in general, have a larger surface area to weight ratio, thus requiring relatively more heating energy from external sources.

Table 4.7- Percentage changes in impact category metrics for entire males scenarios compared to the baseline, reported per kg of live weight at the farm gate

Alternative management strategy	Impact Category	SCN01	SCN02	SCN03	SCN04	SCN05
Entire Males	IPCC GWP 100a (kg CO_2e)	0.176	2.144	2.092	-0.062	1.531
	Non-renewable (MJ)	1.885	3.738	3.748	1.719	2.767
	Water (m^3)	-4.613	-2.244	-2.294	-4.488	-2.306

Uncertainty analysis

Detailed results of uncertainty analysis are presented in Table 4.8 through Table 4.10, which shows the output from 1000 Monte Carlo runs in which the background processes were held invariant for the comparison. Environmental impact categories for each of the management strategies were compared to the baseline and confidence interval were created. For example, for no ractopamine management practice for SCN03 the results show that the production without ractopamine leads to increase in GHG emissions for 92% of the simulations and that the mean difference in GHG emissions for all 1000 simulations, was increase of 0.167 kg CO_2e from reduced feed efficiency.

Figure 4.5 through Figure 4.13 summarize the results of the Monte Carlo simulations for each alternative management scenario and for SCN03, SCN04, and SCN05 for three impact categories. These figures each show the baseline result as horizontal blue line and the range of the paired Monte Carlo simulations as box and whisker plot. The interpretation of these graphs is important because this analysis is an indication of the robustness of the conclusions that can be made from the study. This is distinct from any discussion which may result in modification to the parameters used to generate the results. Specifically, the horizontal lines of each box represent the 25th, 50th, and 75th percentiles of the 1000 Monte Carlo simulation runs. The lower and upper colored extensions denote the 10th and 90th percentiles, respectively. Where the simulations represented by the box and whisker lie above the horizontal line, the alternate practice resulted in an increase in environmental impact. For example, consider the no ractopamine scenario for GHG emissions for SCN03 (Figure 4.5). In this scenario the 10th percentile is greater than the baseline. The interpretation of this result is that it can be stated with 90% confidence that production without ractopamine resulted in increase in GHG emissions. Further, as the 50th percentile is approximately 0.08 kg CO_2e higher than baseline, it can be stated with 50% confidence that production without ractopamine will result in at least 0.08 kg CO_2e increase per kg live weight of a pig on average.

Entire Males

Uncertainty analysis for entire males shows that for SCN05 56% of simulations resulted in lower GHG emissions, while for SCN03 and SCN04 56 and 62% of simulations respectively resulted in higher GHG emissions compared to the baseline. For energy use 68, 75, and 62% of simulations for SCN03, SCN04, and SCN05 respectively resulted in higher energy use. Water use however, was consistently lower compared to the baseline for all SCN03, SCN04, and SCN05. Out of 1000 Monte Carlo simulations 20, 22, and 21% of simulations resulted in lower water use compared to the baseline for SCN03, SCN04, and SCN05 respectively. However, box and whisker plots (Figure 4.5 through Figure 4.13) show that for GHG emissions, and energy use for most of the temperature regimes the baseline is either approximately equal to the 50th percentile or is between 50th and 75th percentile. For SCN04 box and whisker plots for energy use show 25th percentile is close to the baseline and therefore, it can be stated with approximately 75% confidence energy use for entire males were higher than baseline for these two scenarios. Contrary to GHG emissions and energy use, for cumulative water use baseline on box and whisker plots was consistently above 75th percentile. Therefore, it can be stated with at least 75% confidence that water use for this alternative management practice was lower than the baseline.

Gestation Pens

For gestation pens all temperature scenarios resulted in lower GHG emissions, energy use, and water use. Mote Carlo simulations showed that 59, 58, and 60% of simulations for SCN03, SCN04, and SCN05 respectively, resulted in lower GHG emissions compared to the baseline. For energy use and water use as well, similar trend in uncertainty analysis results was observed. For energy use 65, 66, and 68% while for water use 57, 61, and 58% of simulations for SCN03, SCN04, and SCN05 respectively resulted in lower impact metrics. However, for all temperature regimes the box and whisker plots show that horizontal line representing baseline is between the 50th and 75th percentile. Therefore it can be stated only with less than 75% confidence that gestation pens led to lower environmental impact across all impact categories for all temperature regimes.

Immunocastration

Uncertainty analysis for immunocastration resulted in lower GHG emissions, energy use, and water use compared to baseline for all temperature regimes. Number of Monte Carlo simulations that resulted in lower impact were 76, 69, and 60% for GHG emissions; 78, 70, and 66% for energy use; and 77, 70, 64% for water use for SCN03, SCN04, and SCN05 respectively. For SCN03 the 75th percentile for GHG emissions is close to the baseline (Figure 4.5). Therefore, it can be stated with at least 75% confidence that for SCN03 immunocastration led to lower GHG emissions. For SCN04 and SCN05 however, the horizontal line for baseline is between 75th and 50th percentile (Figure 4.8, and Figure 4.11). Therefore, there is less than 75% confidence that immunocastration for these temperature regimes led to lower GHG emissions. For energy use for SCN03, SCN04, and energy and water use for SCN05, box and whisker plots show that the baseline is between 75th and 50th percentile. Therefore, there is less than 75% but more than 50% confidence that immunocastration led to lower energy and water use SCN05 and lower energy use for SCN03 and SCN04. Water consumption for SCN03 and SCN04 can be concluded as lower than baseline with approximately 75% confidence.

No growth promoting antimicrobials

Monte Carlo simulations for production without growth promoting antimicrobials showed that 69, 86, and 70% of simulations for GHG emissions, 71, 87, and 73% of simulations for energy use, and 59, 75, and 61% of simulations for water use resulted in higher impact for all impact categories for scenarios SCN03, SCN04, and SCN05 respectively. This increase in the environmental impact was a due to lowered weight gain and feed efficiency that resulted from production without growth promoting antimicrobials. Box and whiskers plot for SCN03, SCN05 (Figure 4.5 and Figure 4.11) show the line for baseline scenario is between 25th and 50th percentile. Therefore, higher GHG emissions for these temperature regimes cannot be concluded enough evidence. However, for SCN04 (Figure 4.8) higher GHG emissions can be concluded with at least 75% confidence. For energy use it can be concluded with at least 75% confidence that not using growth promoting antimicrobials resulted in increased energy use (Figure 4.6, Figure 4.9, and Figure 4.12). Higher water consumption observed for this alternate management practice could not be concluded for any of the temperature regimes (Figure 4.7, Figure 4.10, and Figure 4.13).

No growth promoting or preventive antimicrobial

Uncertainty analysis of alternate management practice of production without growth promoting or preventive antimicrobials showed that for all temperature regimes 100% of simulations resulted in higher GHG emissions, energy use, and water use, except for water use at SCN01 where 98% of simulations resulted in higher water use. This increased environmental impact was a result of reduced weight gain, feed efficiency and higher death rate in nursery and grow-finish barn as a result of not using growth promoting or preventive antimicrobials in production. This lowered feed efficiency and higher death rate means more pigs are needed in the barn to meet production demand. Box and whisker plots for all temperature regimes (Figure 4.5 through Figure 4.13) show that higher environmental impact seen across all impact categories can be concluded with at least 90% confidence, since 10th percentile for this alternate management practice is either close to baseline or above baseline.

Removal of Ractopamine

Uncertainty analysis for production without ractopamine showed that 92, 90, and 68% of Monte Carlo simulations for SCN03, SCN04, and SCN05 respectively resulted in higher GHG emissions compared to baseline (Table 4.8 through Table 4.10). However, box and whisker plots for GHG emissions (Figure 4.5, Figure 4.8, and Figure 4.10) show that increased GHG emission observed in mean LCA comparison can be concluded with approximately 90% confidence for SCN03, SCN04, while for SCN05 this higher GHG emissions cannot be concluded with enough confidence. This increased GHG emissions was a result of lower feed efficiency which also resulted in more number of days required for pigs to reach market weight and higher feed consumption. Number of simulations for which higher impact were observed were 84, 81, and 48% for energy use, and 87, 83, and 62% for water use for SCN03, SCN04, SCN05 respectively

(Table 4.8 through Table 4.10). Unlike other scenarios, only 48% of the MC simulations for SCN05 resulted in higher energy use compared to the baseline, which means for 52% of MC simulations energy use was lower. However, there was increase in GHG emissions for no ractopamine scenario for SCN05 and lower energy use was contradictory to higher GHG emissions observed. Increase in cumulative energy and water consumption can be concluded with at least 75% confidence for SCN03 and SCN04 only.

Table 4.8- Uncertainty analysis results for alternate management practices for SCN03, with a 95% confidence interval (95% of the simulations fall between 10% and 90%)

Alternative Management Strategy	Impact category	Alternative Exceeds Baseline	Mean Exceedance	SD	COV	10%	90%
Immunocastration	IPCC GWP 100a	24%	-0.083	-0.12	-144%	-0.317	0.162
	Non-renewable, fossil	22%	-0.601	-0.805	-134%	-2.27	1.01
	Water	23%	-0.006	-0.008	-136%	-0.022	0.009
No Ractopamine	IPCC GWP 100a	92%	0.167	-0.12	72%	-0.064	0.403
	Non-renewable, fossil	84%	0.737	-0.783	106%	-0.792	2.32
	Water	87%	0.009	-0.009	91.4%	-0.007	0.027
No GP Antibiotics	IPCC GWP 100a	69%	0.06	-0.12	202%	-0.178	0.313
	Non-renewable, fossil	71%	0.445	-0.988	222%	-1.14	2.06
	Water	59%	0.002	-0.008	485%	-0.015	0.018
No GP No Prev. Antibiotics	IPCC GWP 100a	100%	0.519	-0.146	28%	0.233	0.81
	Non-renewable, fossil	100%	3.63	-1.1	30%	1.68	5.87
	Water	100%	0.024	-0.009	39%	0.006	0.042
Gestation Pens	IPCC GWP 100a	41%	-0.033	-0.188	-354%	-0.269	0.193
	Non-renewable, fossil	35%	-0.311	-0.784	-252%	-1.85	1.22
	Water	43%	-0.001	-0.008	-614%	-0.017	0.016
Entire Males	IPCC GWP 100a	56%	0.017	-0.199	703%	-0.213	0.26
	Non-renewable, fossil	68%	0.408	-0.811	199%	-1.17	2.03
	Water	20%	-0.007	-0.008	-115%	-0.023	0.008

Table 4.9- Uncertainty analysis results for alternate management practices for SCN04, with a 95% confidence interval (95% of the simulations fall between 10% and 90%)

Alternative Management Strategy	Impact category	Alternative Exceeds Baseline	Mean Exceedance	SD	COV	10%	90%
Immunocastration	IPCC GWP 100a	31%	-0.063	-0.134	-212%	-0.329	0.204
	Non-renewable, fossil	30%	-0.421	-0.803	-191%	-2.02	1.16
	Water	30%	-0.005	-0.009	-190%	-0.022	0.011
No Ractopamine	IPCC GWP 100a	90%	0.178	-0.137	77%	-0.085	0.433
	Non-renewable, fossil	81%	0.755	-0.86	114%	0.845	2.25
	Water	83%	0.009	-0.01	103%	-0.01	0.028
No GP Antibiotics	IPCC GWP 100a	86%	0.14	-0.129	93%	-0.096	0.389
	Non-renewable, fossil	87%	0.876	-0.777	89%	-0.59	2.46
	Water	75%	0.006	-0.008	149%	-0.011	0.023
No GP No Prev. Antibiotics	IPCC GWP 100a	100%	0.583	-0.162	28%	0.257	0.903
	Non-renewable, fossil	100%	3.74	-1.05	28%	1.76	6.1
	Water	100%	0.025	-0.01	39%	0.007	0.045
Gestation Pens	IPCC GWP 100a	42%	-0.035	-0.133	-380%	-0.29	0.233
	Non-renewable, fossil	34%	-0.334	-0.816	-244%	-1.87	1.22
	Water	39%	-0.002	-0.008	-457%	-0.019	0.016
Entire Males	IPCC GWP 100a	62%	0.035	-0.129	374%	-0.233	0.282
	Non-renewable, fossil	75%	0.525	-0.799	152%	-1.13	2.07
	Water	22%	-0.006	-0.008	134%	-0.024	0.011

Table 4.10- Uncertainty analysis results for alternate management practices for SCN05, with a 95% confidence interval (95% of the simulations fall between 10% and 90%)

Alternative Management Strategy	Impact category	Alternative Exceeds Baseline	Mean Exceedance	SD	COV	10%	90%
Immunocastration	IPCC GWP 100a	40%	-0.032	-0.143	-452%	-0.299	0.253
	Non-renewable, fossil	34%	-0.319	-0.789	-248%	-1.81	1.22
	Water	36%	-0.003	-0.009	-330%	-0.019	0.015
No Ractopamine	IPCC GWP 100a	68%	0.074	-0.149	201%	-0.204	0.376
	Non-renewable, fossil	48%	-0.064	-0.8	-1260%	-1.56	1.57
	Water	62%	0.003	-0.009	312%	-0.014	0.021
No GP Antibiotics	IPCC GWP 100a	70%	0.071	-0.143	200%	-0.219	0.345
	Non-renewable, fossil	73%	0.478	-0.79	165%	-1.07	1.93
	Water	61%	0.002	-0.009	359%	-0.015	0.019
No GP No Prev. Antibiotics	IPCC GWP 100a	100%	0.643	-0.169	26%	0.305	1.01
	Non-renewable, fossil	100%	3.72	-1.09	29%	1.83	6.2
	Water	100%	0.027	-0.01	36%	0.009	0.046
Gestation Pens	IPCC GWP 100a	40%	-0.032	-0.144	-455%	0.315	0.262
	Non-renewable, fossil	32%	-0.323	-0.779	-241%	-1.84	1.23
	Water	42%	-0.002	-0.008	547%	-0.019	0.015
Entire Males	IPCC GWP 100a	44%	-0.019	-0.145	-771%	-0.305	0.281
	Non-renewable, fossil	62%	0.229	-0.803	351%	-1.33	1.84
	Water	21%	-0.007	-0.008	-127%	-0.023	0.01

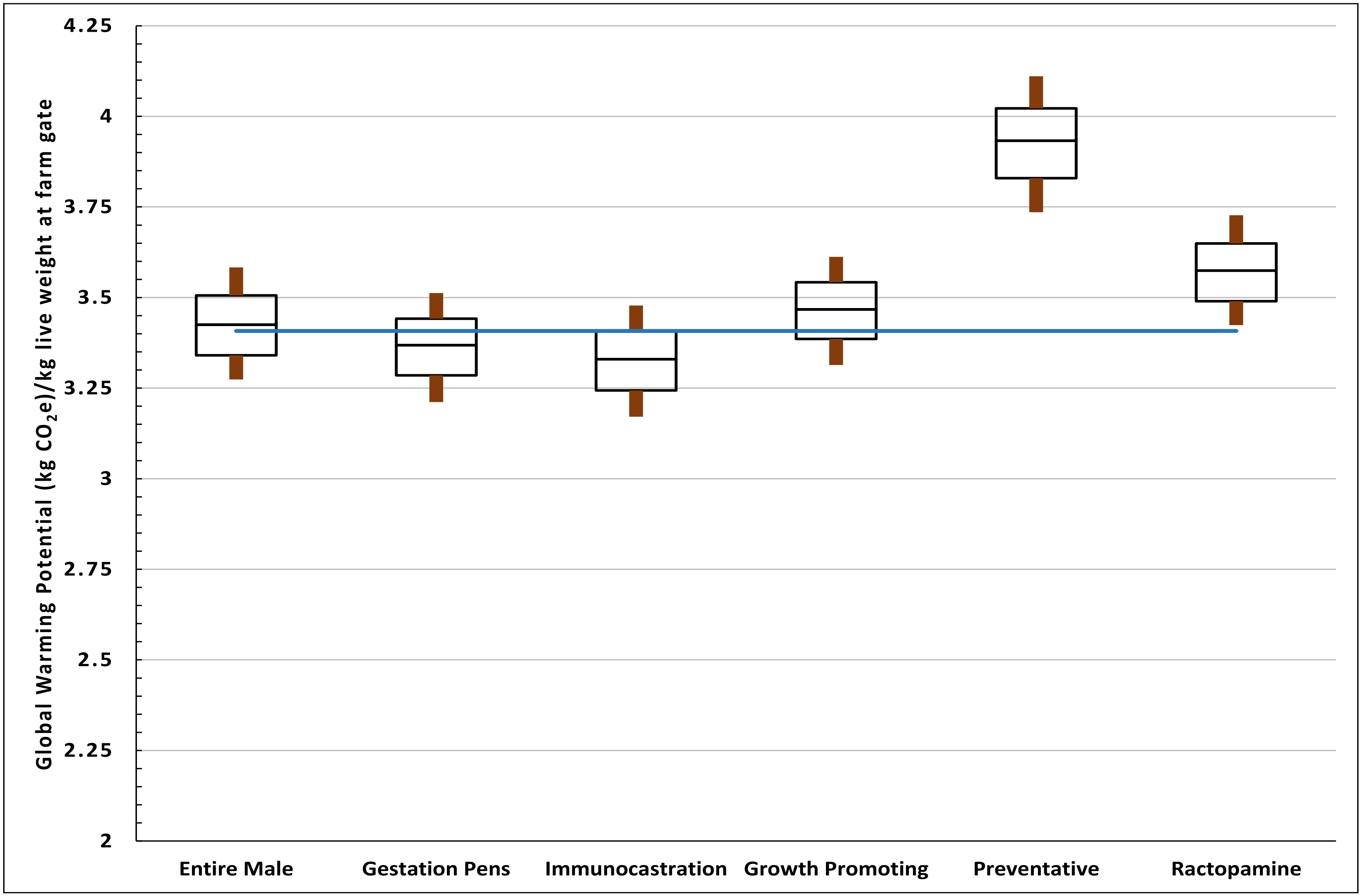

Figure 4.5- Estimated potential change in greenhouse gas emissions for alternate management practice for SCN03. The horizontal line represents the project baseline production scenario

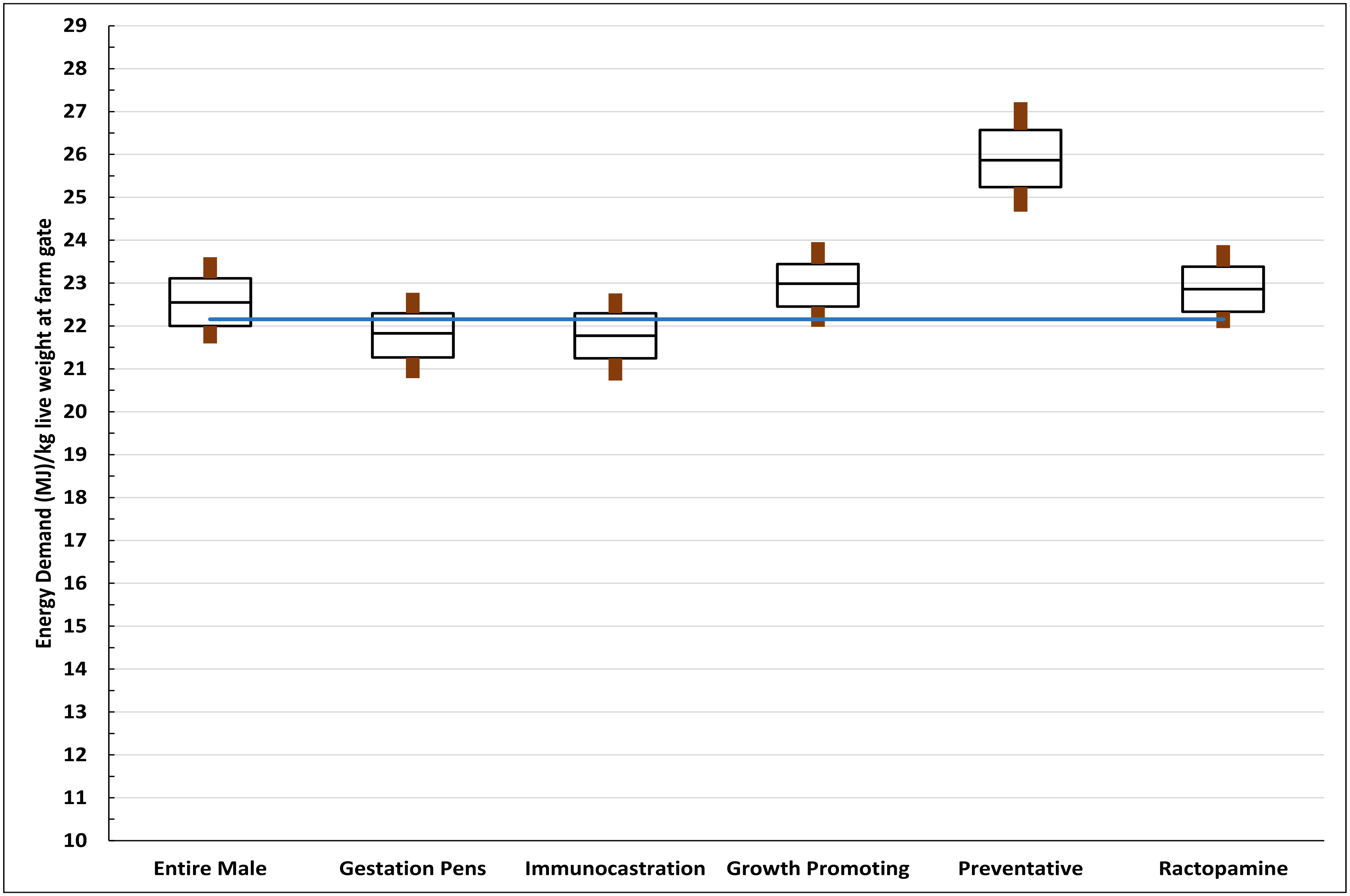

Figure 4.6- Estimated potential change in non-renewable energy demand for alternate management practice for SCN03. The horizontal line represents the project baseline production scenario

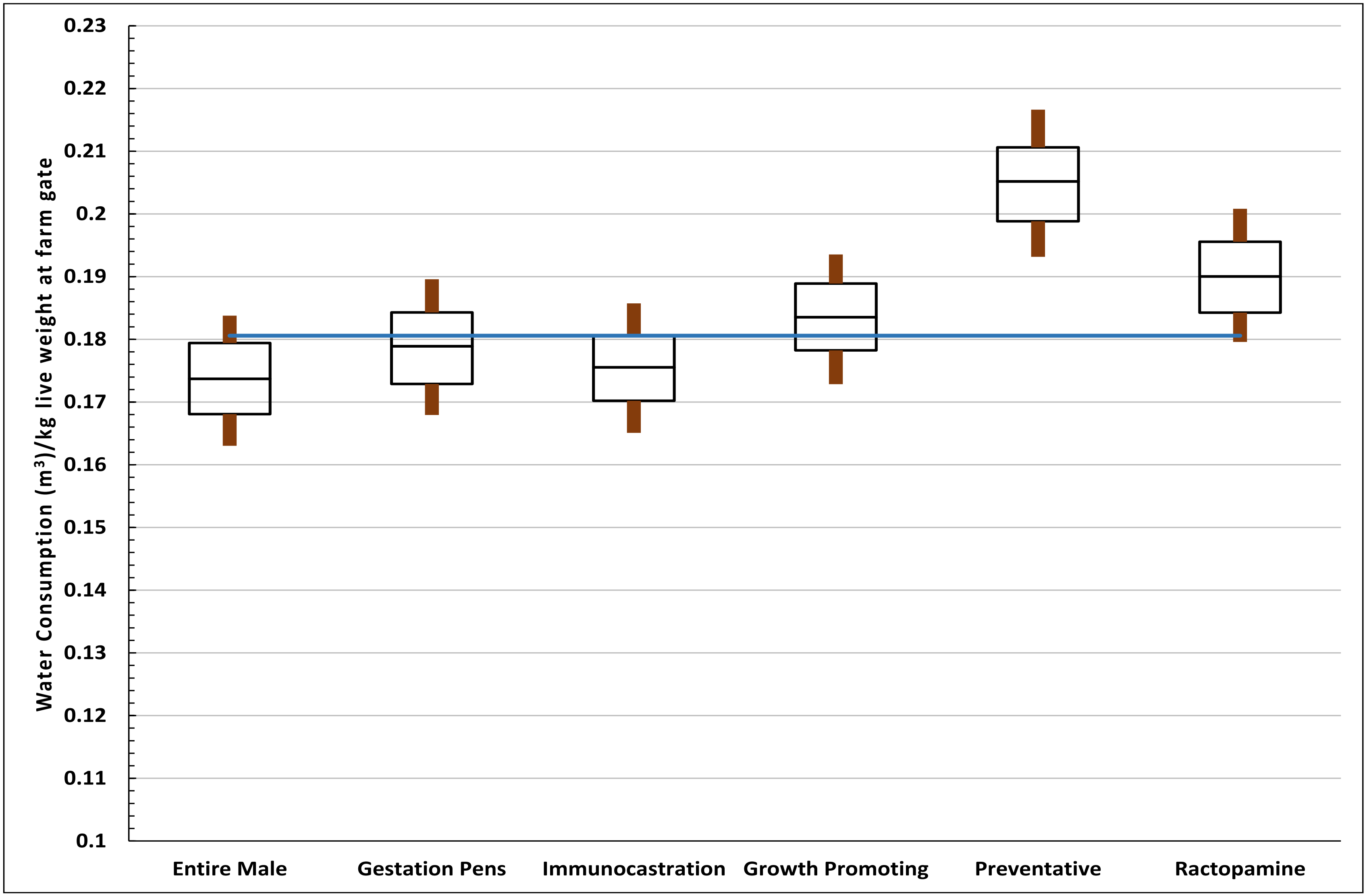

Figure 4.7- Estimated potential change in water use for alternate management practice for SCN03. The horizontal line represents the project baseline production scenario

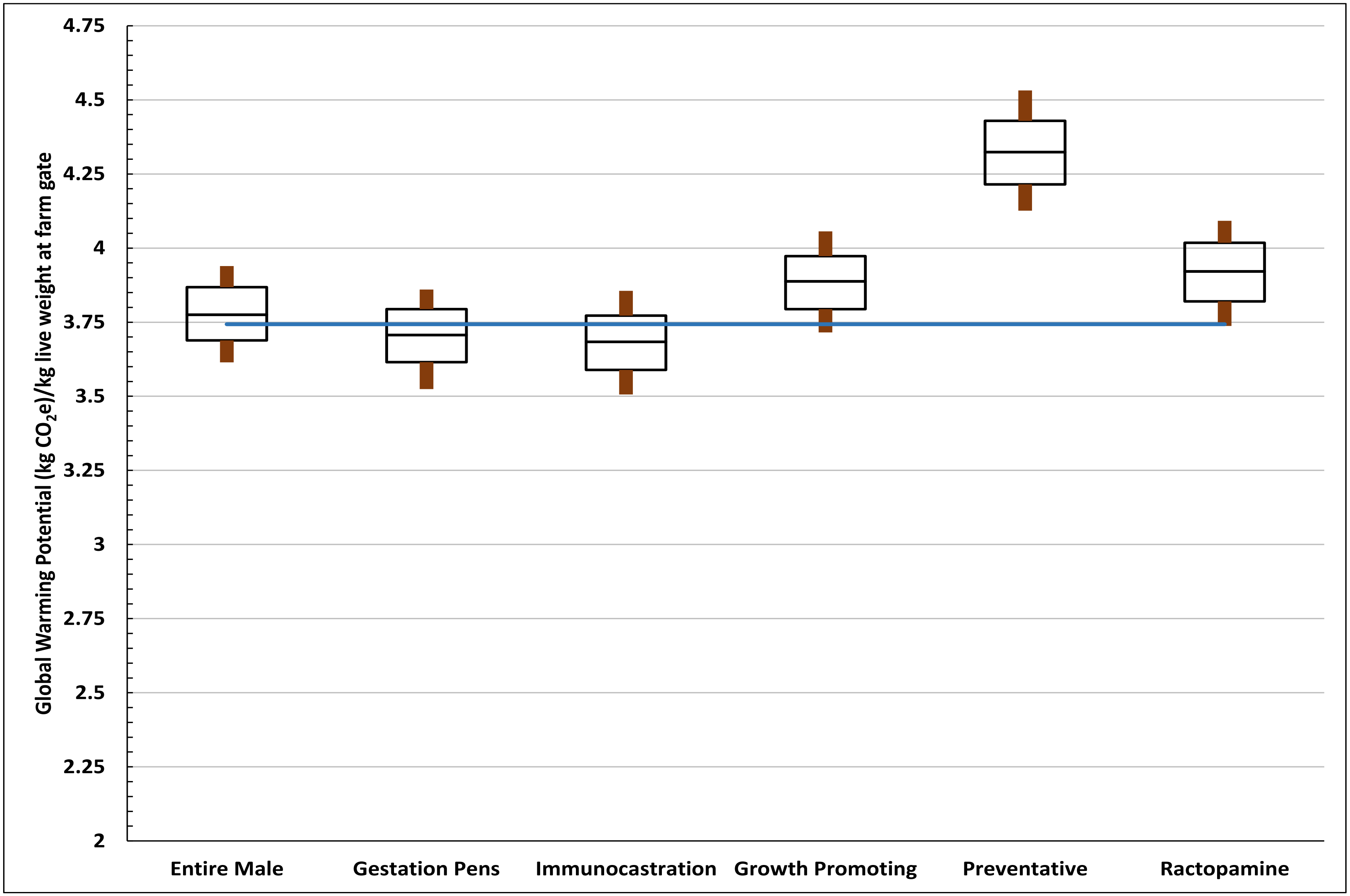

Figure 4.8- Estimated potential change in greenhouse gas emission for alternate management practice for SCN04. The horizontal line represents the project baseline production scenario

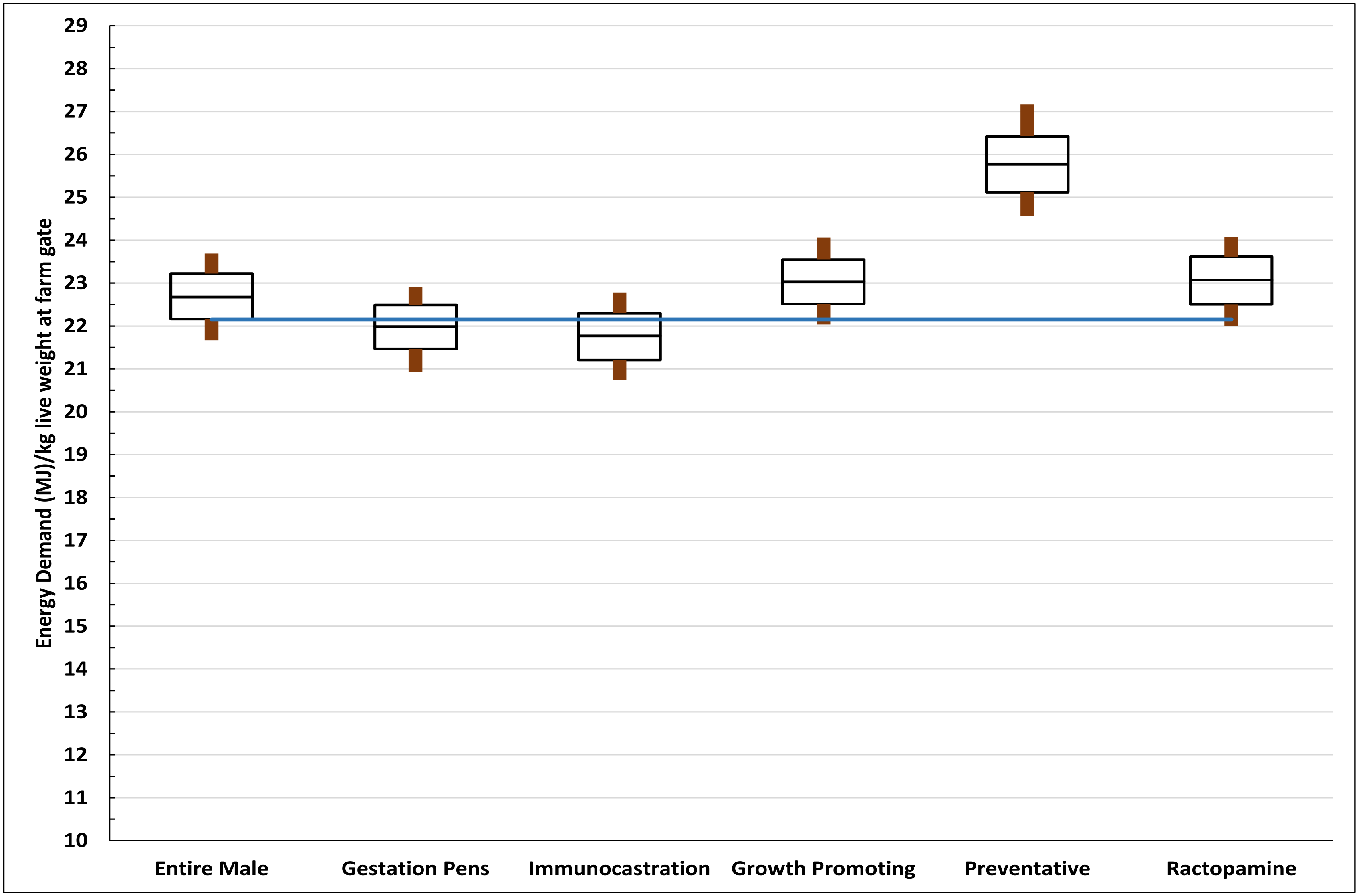

Figure 4.9- Estimated potential change in non-renewable energy demand for alternate management practice for SCN04. The horizontal line represents the project baseline production scenario

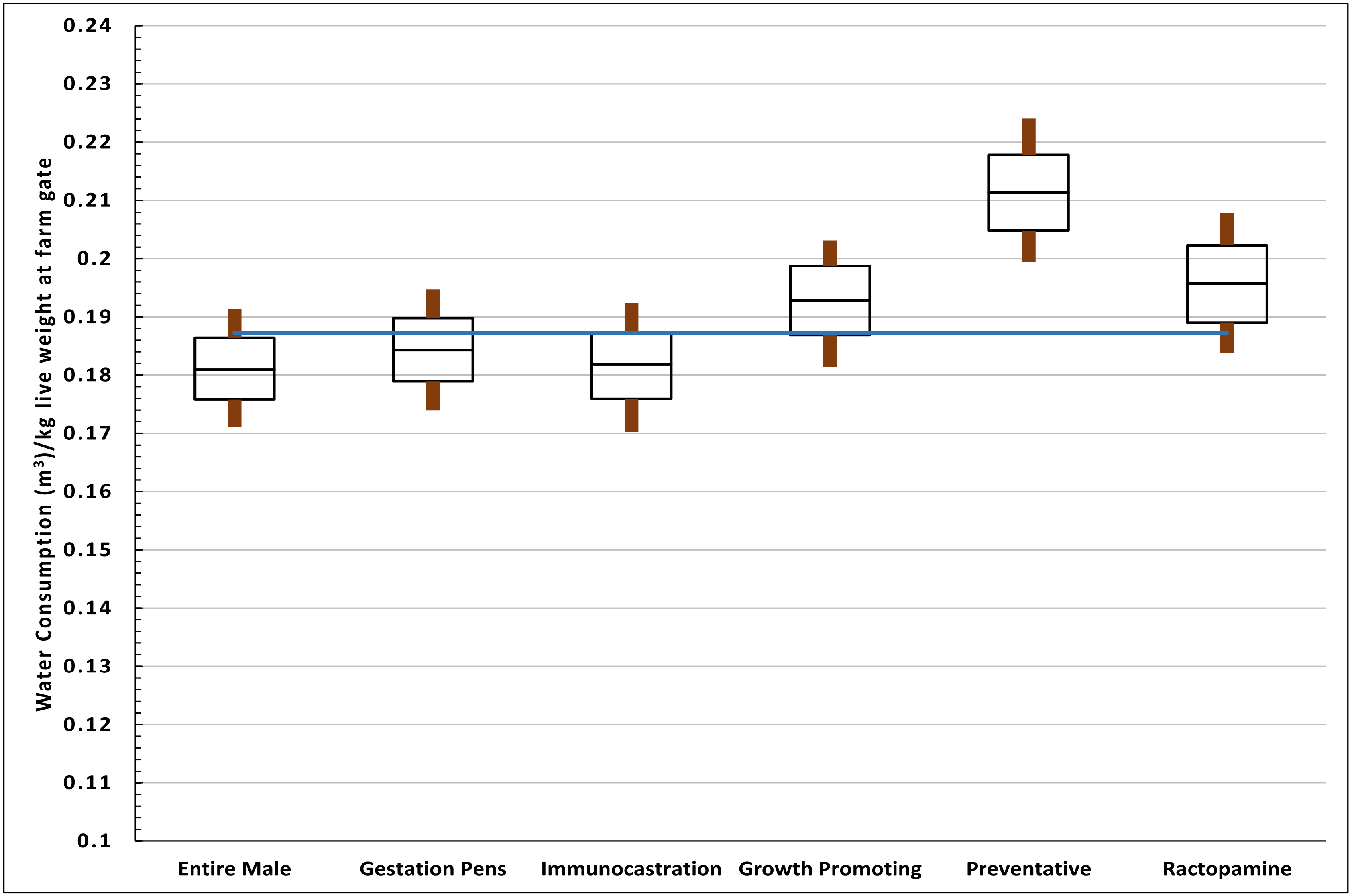

Figure 4.10- Estimated potential change in water use for alternate management practice for SCN04. The horizontal line represents the project baseline production scenario

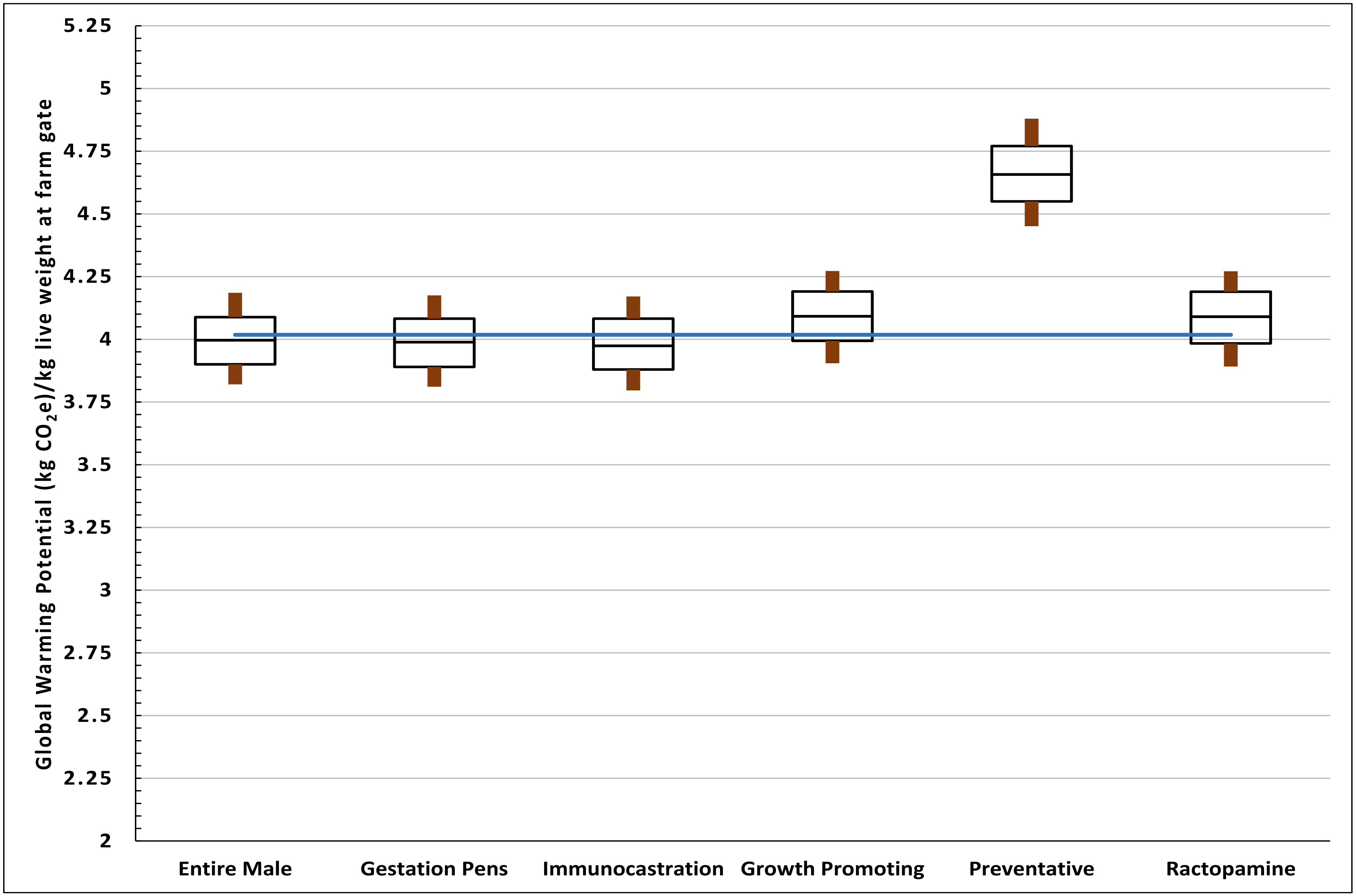

Figure 4.11- Estimated potential change in greenhouse gas emissions for alternate management practice for SCN05. The horizontal line represents the project baseline production scenario

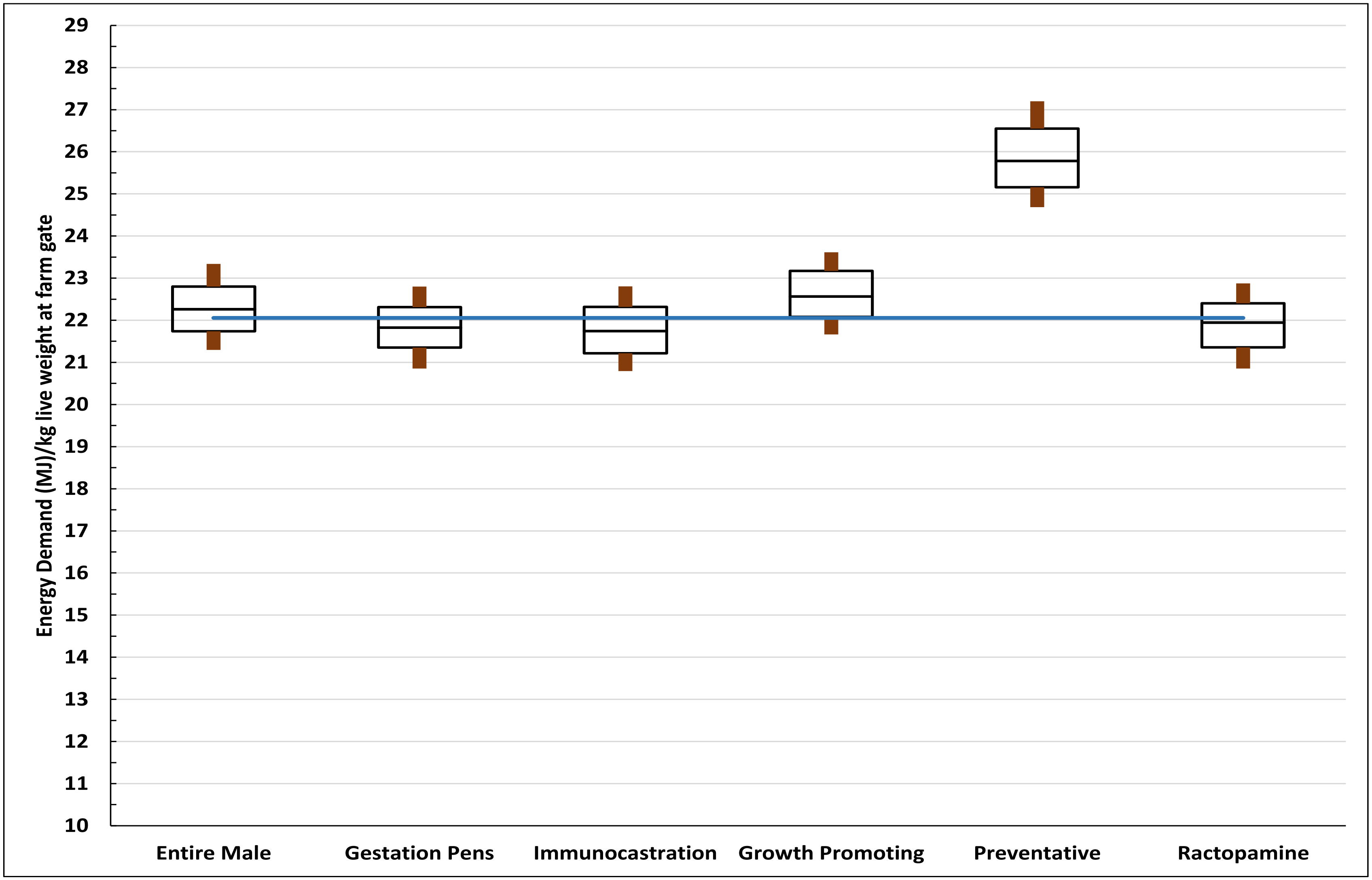

Figure 4.12- Estimated potential change in non-renewable energy demand for alternate management practice for SCN05. The horizontal line represents the project baseline production scenario

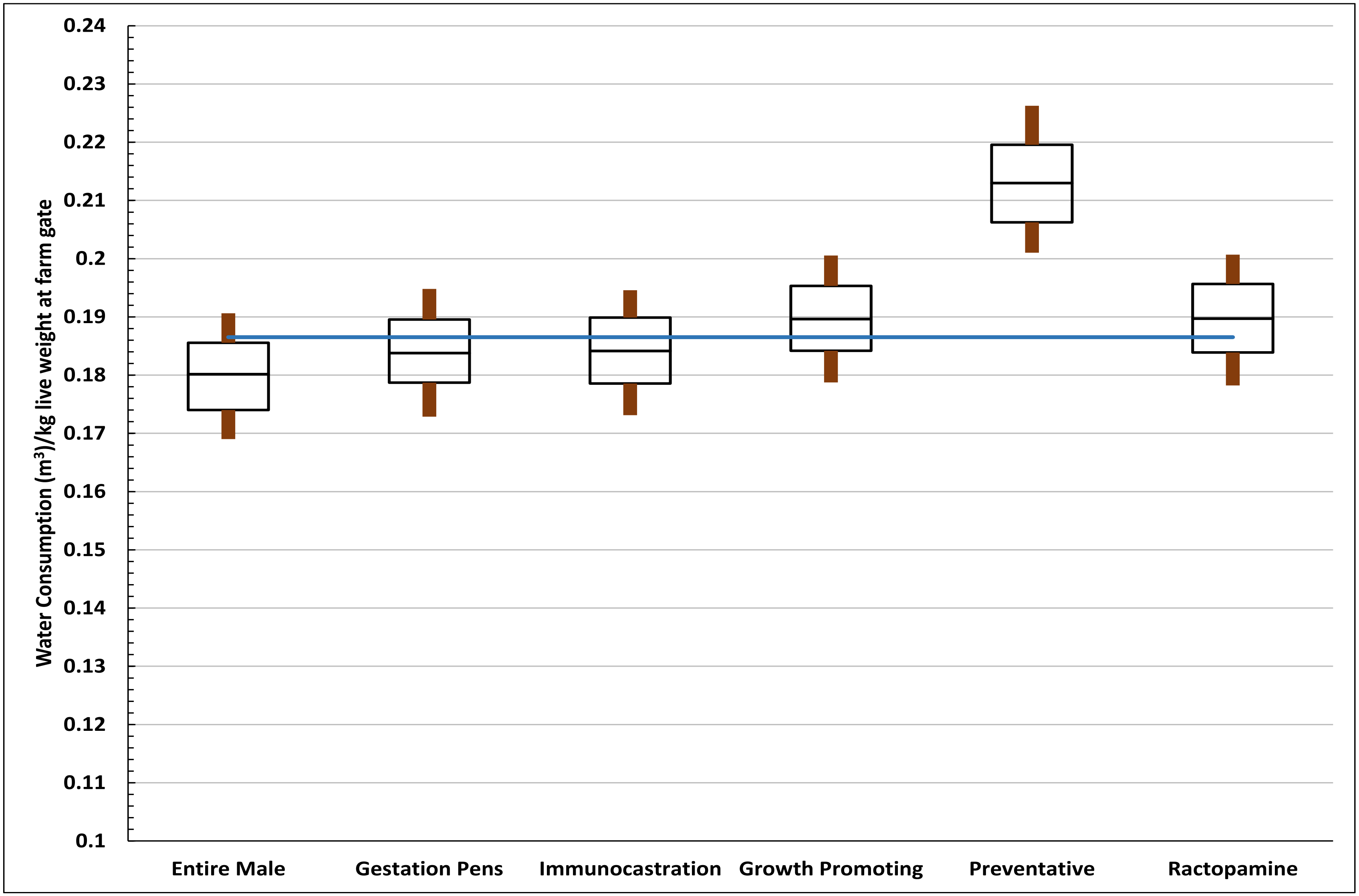

Figure 4.13- Estimated potential change in water use for alternate management practice for SCN05. The horizontal line represents the project baseline production scenario

Chapter 5 Conclusion and recommendations

Objective of the work

There is a mounting pressure on pork industry to show improvements across sustainability metrics and animal welfare. To achieve these changes to some of the management practices in the pork industry might be necessary. Besides these voluntary steps that the industry might require to take, there have been few mandates, which were sanctioned by few states in the United States. For instance, use of sow gestation crates was banned in Florida in 2002 and in Arizona in 2006 (Mench 2008). Smithfield Foods in 2007 decided to phase out gestation stalls on company-owned farms over next 10 years and replace them with pens. However, before any major changes are made to the production practices, it is important to assess the impacts of those changes on sustainability metrics to make sure we move forward towards making agriculture more sustainable. Therefore, the objective of this study was to quantify differences in greenhouse gas (GHG) emissions, cumulative energy use, and water consumption between current practices and proposed alternate management systems using Life Cycle Assessment (LCA). The scope of this study was set to "cradle to farm gate" with a functional unit of one kg live weight at the farm gate.

Summary of approach and findings

In this study all the test scenarios were compared with common baseline management scenario, which was defined to represent current industry standards in pork production. Each test scenario evaluated only one management practice, where one key element was different from the baseline scenario. Inputs to Pig Production Environmental Footprint (PPEF) model were manipulated to achieve expected changes in the pig growth for each scenario. The results of PPEF model were used as life cycle inventory (LCI) to the life cycle analysis model developed in

SimaPro V7.3 (Pre' Consultants, The Netherlands). Environmental impacts associated with each member of the LCI were estimated using unit processes available in the Ecoinvent database in the SimaPro.

Six management practices- Entire males, gestation pens, immunocastration, production without growth promoting antimicrobials (AGP), production without AGP or preventive antimicrobials, and production without ractopamine- were evaluated for five temperature regimes, which included

1. Fixing temperature in grow and sow growth sub-module at 20°C (SCN01); using geographical location: Wright County, Iowa
2. Fixing temperature in grow and sow growth sub-module at 25°C (SCN02); using geographical location: Wright County, Iowa
3. Using Typical Meteorological Year (TMY) for regulating temperature in the barn at Wright County, Iowa (SCN03)
4. Using TMY for regulating temperature in the barn at Texas County, Oklahoma (SCN04)
5. Using TMY for regulating temperature in the barn at Wake County, North Carolina (SCN05)

Life cycle assessment of six production strategies for three environmental impact categories yielded a range of results. For entire males, when compared with the baseline, higher GHG emissions were observed SCN01 (0.176%), SCN02 (2.144%), SCN03 (2.092%), and SCN05 (1.531%), while lower GHG emissions were observed for SCN04 (-0.062%). Energy and water use was consistently higher for all temperature regime for this alternative practice. For gestation pens scenario, lower GHG emissions, energy use, and water use were observed for all temperature regimes, compared to the baseline. The most reduction in GHG emissions, energy use and water use of 0.973, 1.499, and 0.972% respectively were observed for SCN03. Using immunocastration instead of surgical castration resulted in lower GHG emissions, energy use, and water use across all temperature regimes with maximum reduction of 3.422, 3.444 and 4.124% respectively observed for SCN01. Production without growth promoting antimicrobials and without growth promoting and preventive antimicrobials both resulted in increased GHG emissions, energy use, and water use. Without growth promoting antimicrobial largest increase in impact categories of 4.197, 4.311, and 4.103% was observed for SCN04. Among all the test scenarios, production without growth promoting and preventive antimicrobials resulted in the largest increase in sustainability metrics. For SCN05 increase in GHG emissions, energy use and water use was 17.934, 18.298, and 16.536% for this test scenario. Production without ractopamine increased GHG emissions, energy use, and water use with 6.515, 4.867, and 7.518% increase in GHG emissions, energy use and water use respectively observed for SCN03.

Hypotheses testing

The differences to sustainability metrics observed in comparative analyses represented differences in the means for each impact category. In order to validate the results uncertainty analysis was performed using Monte Carlo simulations (MSC). Results of these Monte Carlo simulations were used to test the hypotheses. Different temperature scenarios (SCN01 to SCN05) were formulated in this study to understand the effect of temperature on results of LCA model. It was observed that temperature affected results of LCA study mainly because PPEF model was sensitive to temperature fluctuations. However, the objective of this study was to determine differences in sustainability metrics associated with changes in management practices in swine production. Therefore, a single scenario formulated for Wright County, Iowa that used TMY (SCN03) was used for hypotheses testing. The hypotheses were tested using one-tail paired t-test with $\alpha = 0.05$. Data obtained from Monte Carlo simulations for each alternative management practice and baseline were used for paired t-test. The hypotheses used in this study are restated below with conclusions drawn from the statistical tests.

H_0: Changing management practices in the pork production in the US does not affect impact category metrics used for sustainability assessment

H_a: Changing management practices in the pork production in the US affects impact category metrics used for sustainability assessment

Comparative LCA showed that alternative management practices resulted in increased estimated GHG emissions and cumulative energy use for entire males, production without antimicrobials, production without preventive antimicrobials, and production without ractopamine scenarios. Use of gestation pens and immunocastration resulted in lower estimated GHG emissions and cumulative water use compared to the baseline. Estimated water use compared to the baseline was lower for production of entire males, use of gestation pens, and use of immunocastration scenarios, while it was higher for production without growth promoting antimicrobials, production without preventive antimicrobials, and production without ractopamine scenarios. The results of one-tail paired t-test indicated that these changes observed for all impact categories and alternative management practices were statistically significant at $P<0.001$. Therefore, there exists enough evidence to reject the null hypothesis that changing management practices in the pork production in the US does not affect impact category metrics used for sustainability assessment.

Sources of errors and uncertainties

The most potential source of uncertainty in this analysis was from the production model used for simulation of swine production facility. The PPEF model uses growth equations developed by National Resource Council (NRC). These equations do not account for influence of genetic differences in various breeds of pigs on growth rate, feed conversion, and lean content of meat. To compensate for this the same model was used for simulating all management practices, including the baseline. This ensured that errors did not introduce bias into the comparison. The growth rate, as determined by PPEF model, is extremely sensitive to barn temperature and small differences in the temperature were observed to impact growth of pigs substantially, especially in heavier pigs. Therefore, more work is required to understand influence of genetic differences and temperature on model parameters in order to reduce the errors.

The other source of uncertainty in this analysis was from the data used to parameterize the model and analyze the system. A few parameters in the PPEF model were changed, especially for use of gestation pens and production without antimicrobials, using data obtained from various sources. Because the model is known to be influenced by growth rate, feed conversion ratio, and mortality rate, any uncertainty in data used to alter the model parameters would affect the results of PPEF model. Feed formulation used in this study was developed by animal nutritionists at the University of Arkansas. In LCA, feed was one of the main components driving carbon footprint and therefore, uncertainty in feed could also lead to erroneous results.

Concluding remarks

Changes to the sustainability metrics for all alternative management practices compared to the baseline were statistically significant. However, the results of uncertainty analyses should also be used to interpret differences in means observed in this study, especially where the differences are very small. These results are the product of simulation of pork production strategies combined with the unit process LCAs. These models are very sensitive to the time in the barn at each growth stage, rates of conversion of feed to the lean meat, and mortality rates. Also, five temperature scenarios used in this LCA work, along with the simulations conducted to evaluate temperature sensitivity of PPEF model show that the NRC growth models used to estimate pig growth is extremely sensitive to the temperature. Model sensitivity and uncertainty are difficult to characterize due to the limited observational data for which the pork production models were calibrated, and the limited Life Cycle Inventory data for alternative production strategies. It is therefore important to interpret these results with caution. Results of this study should be interpreted in general trend, rather than absolute numbers, observed in the study.

Recommendations

Considering high sensitivity of NRC growth models to the temperature in the barn, these growth models should be tested for accuracy of calibration of equations used to capture the effect of temperature inside the barn on pig growth. Testing of these equations for their accuracy was out of the scope of our study. The NRC growth models fail to capture genetic differences and improvements in various breeds of pigs. The influence of genetic differences in various breeds of pigs on NRC growth models should be studied.in order to capture these differences. Results of LCA study are only as good as the life cycle inventory data used as an input to the model and therefore, good quality life cycle inventory data for alternative management practices should be used for LCA study

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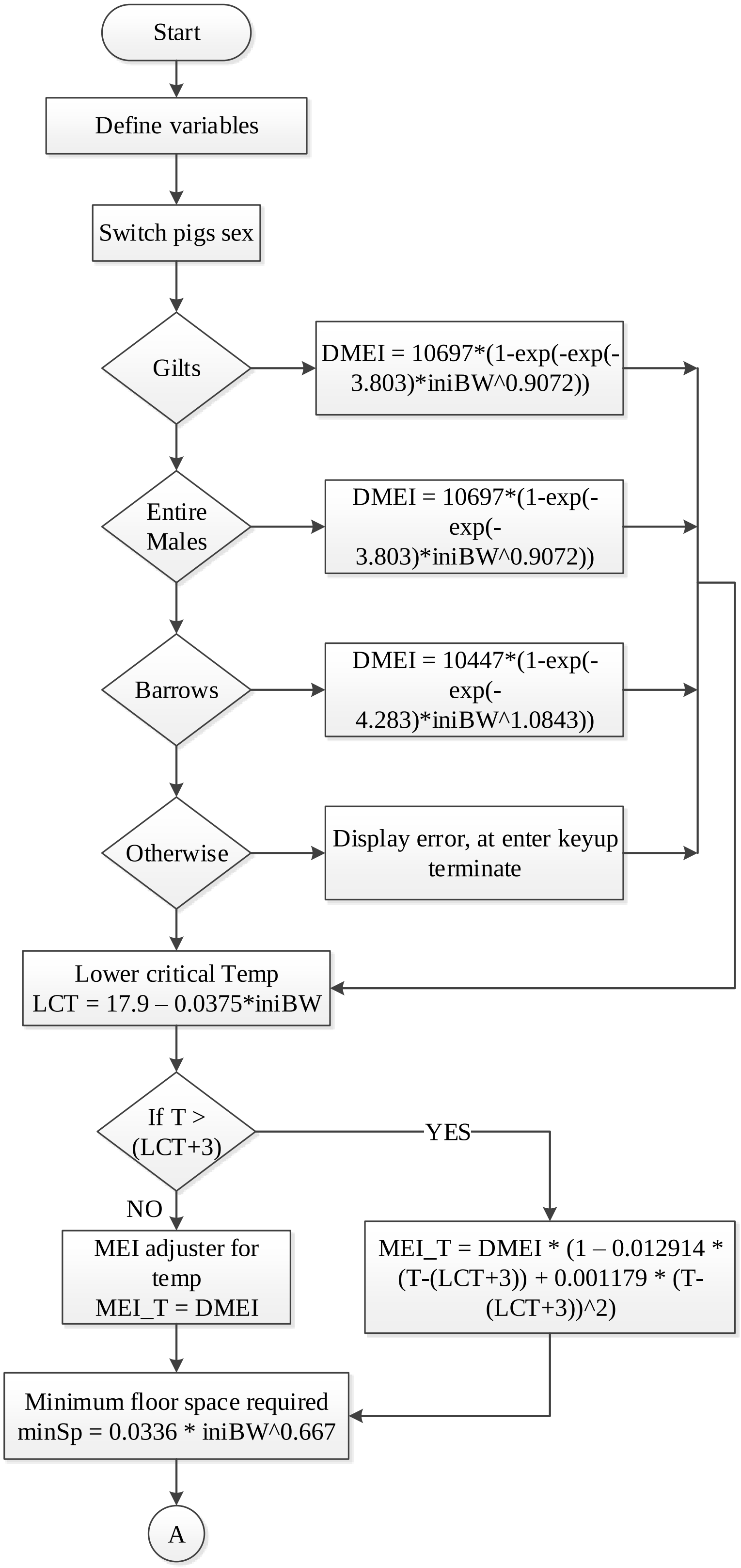
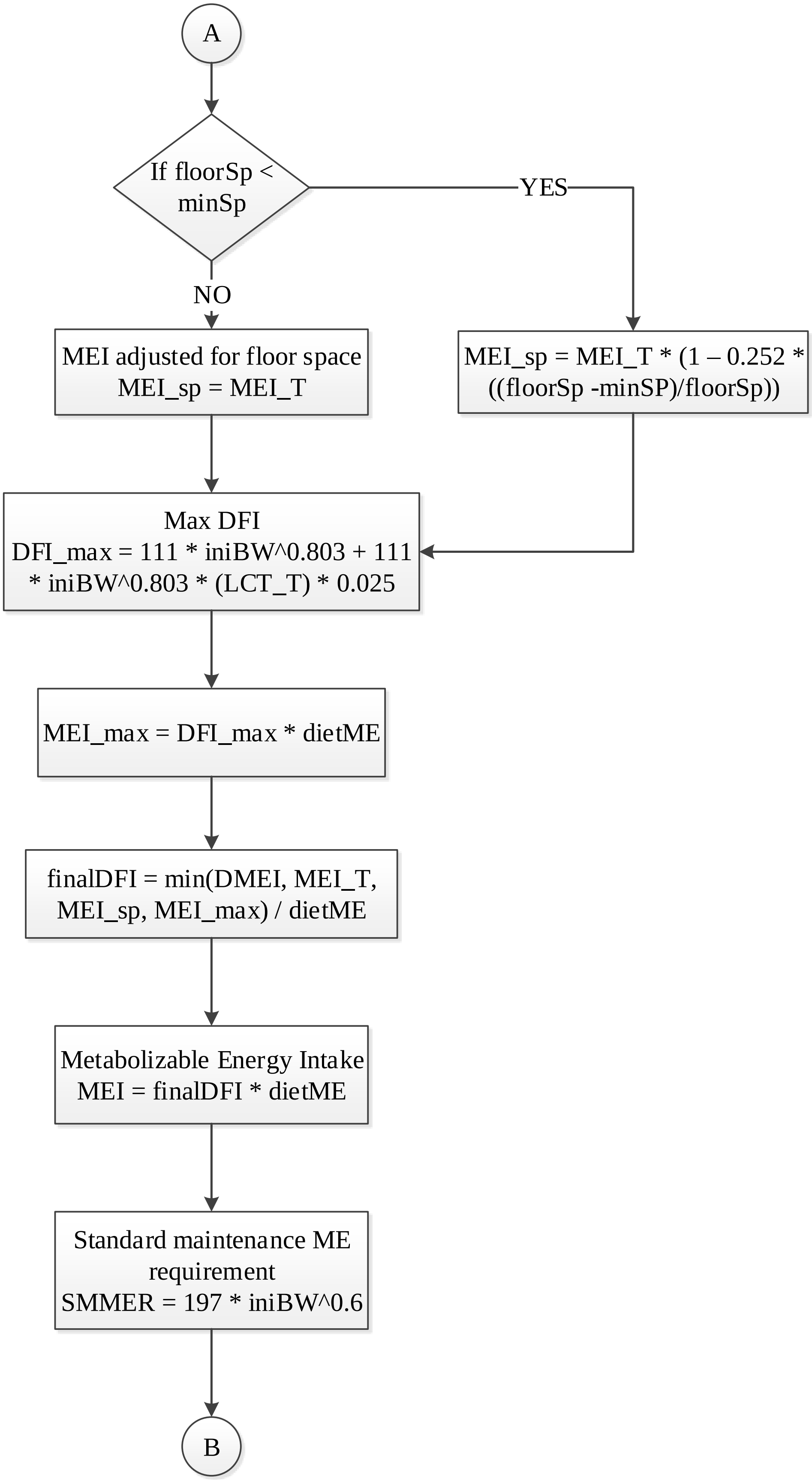
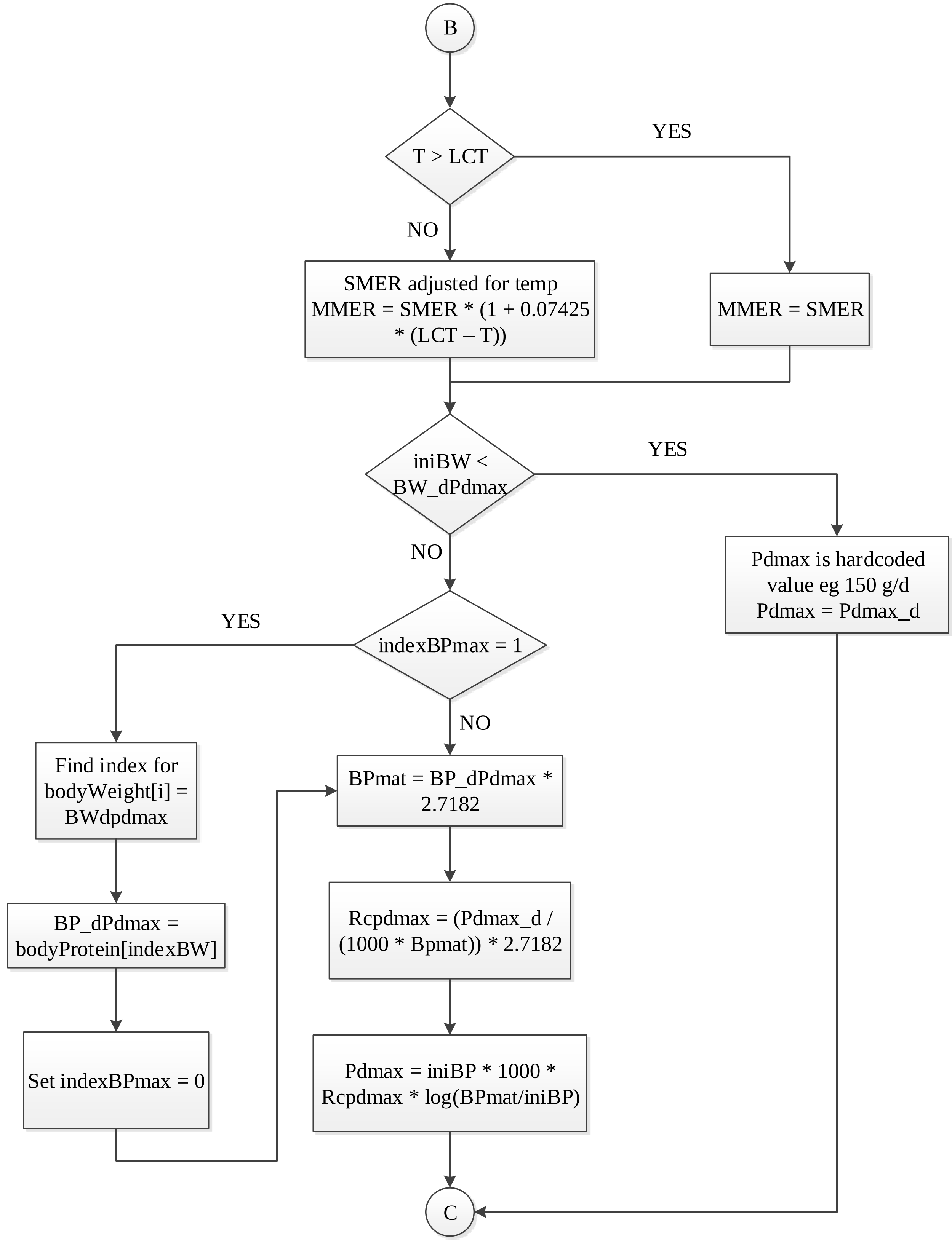
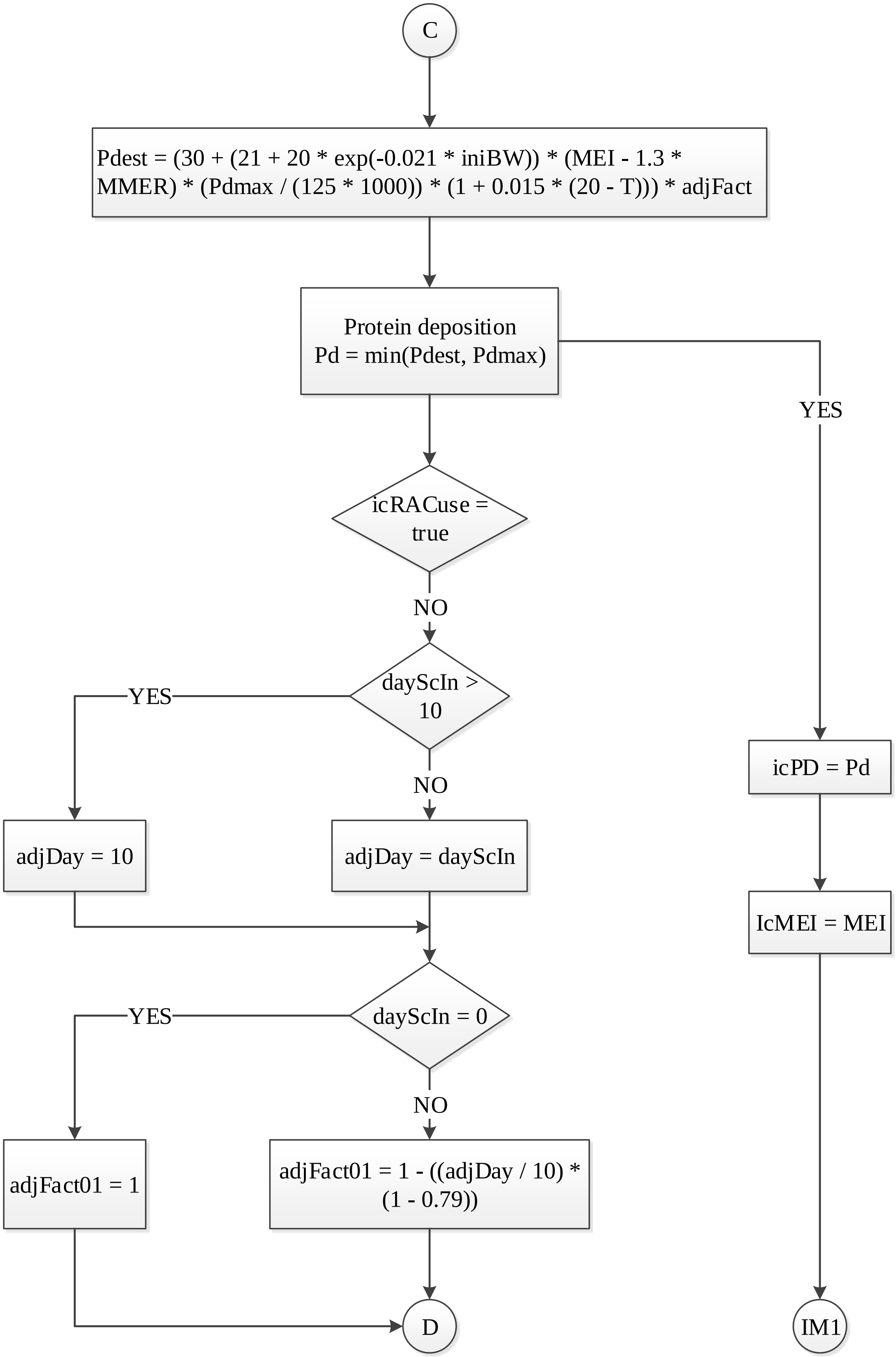
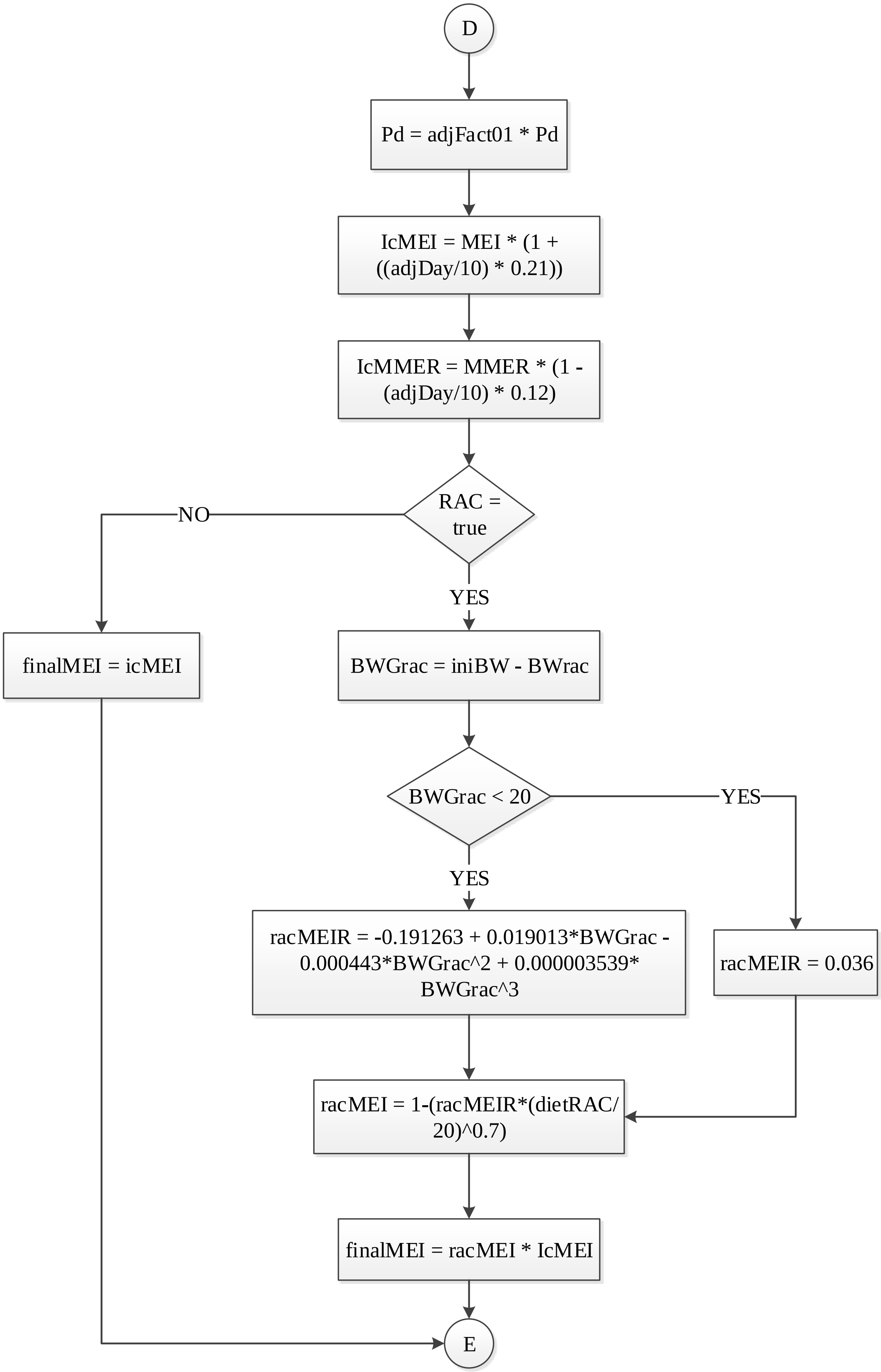
Appendix A: National Research Council model for growth of grow-finish pigs implemented in Pork Production Environmental Footprint (PPEF) model

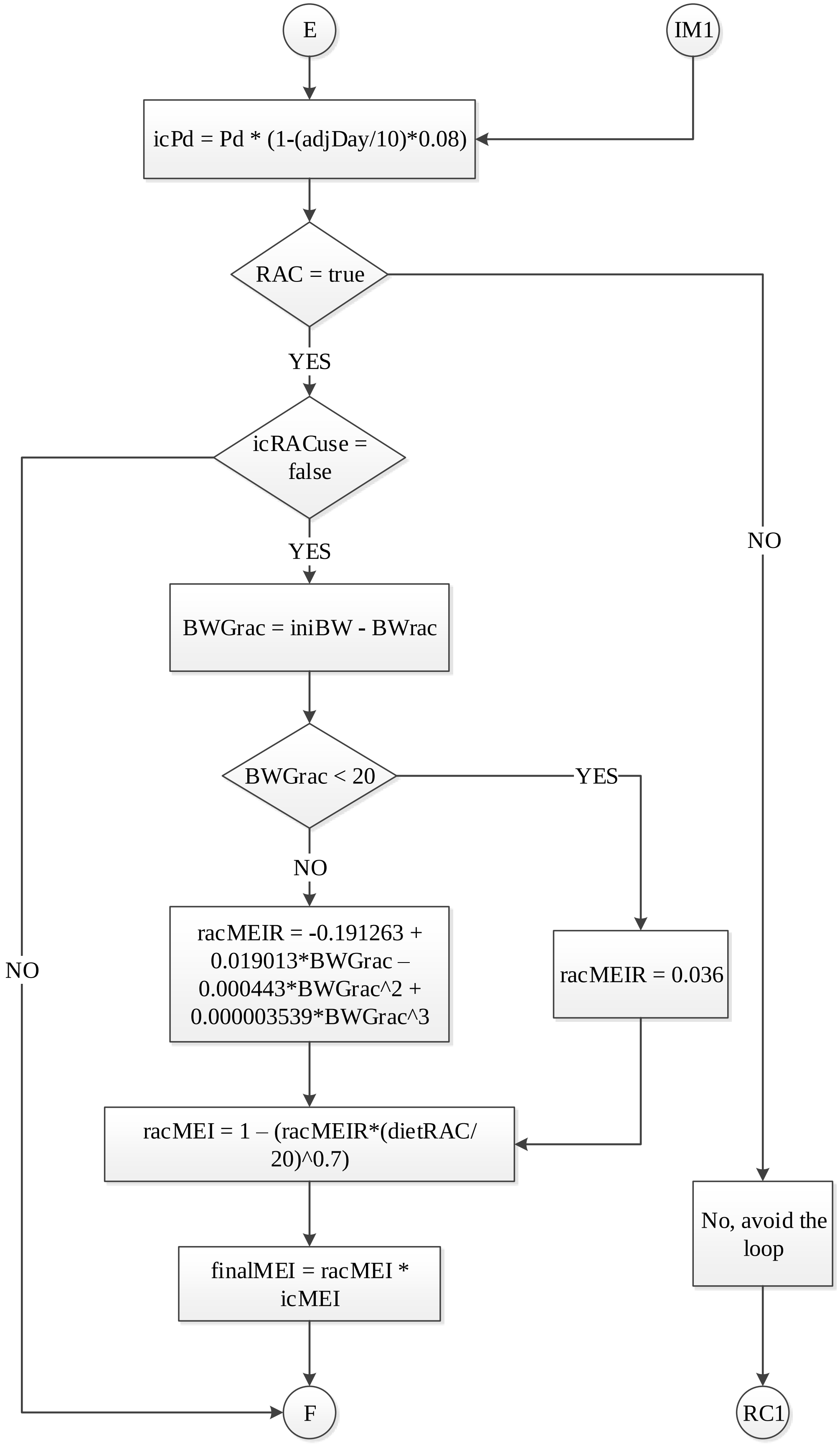


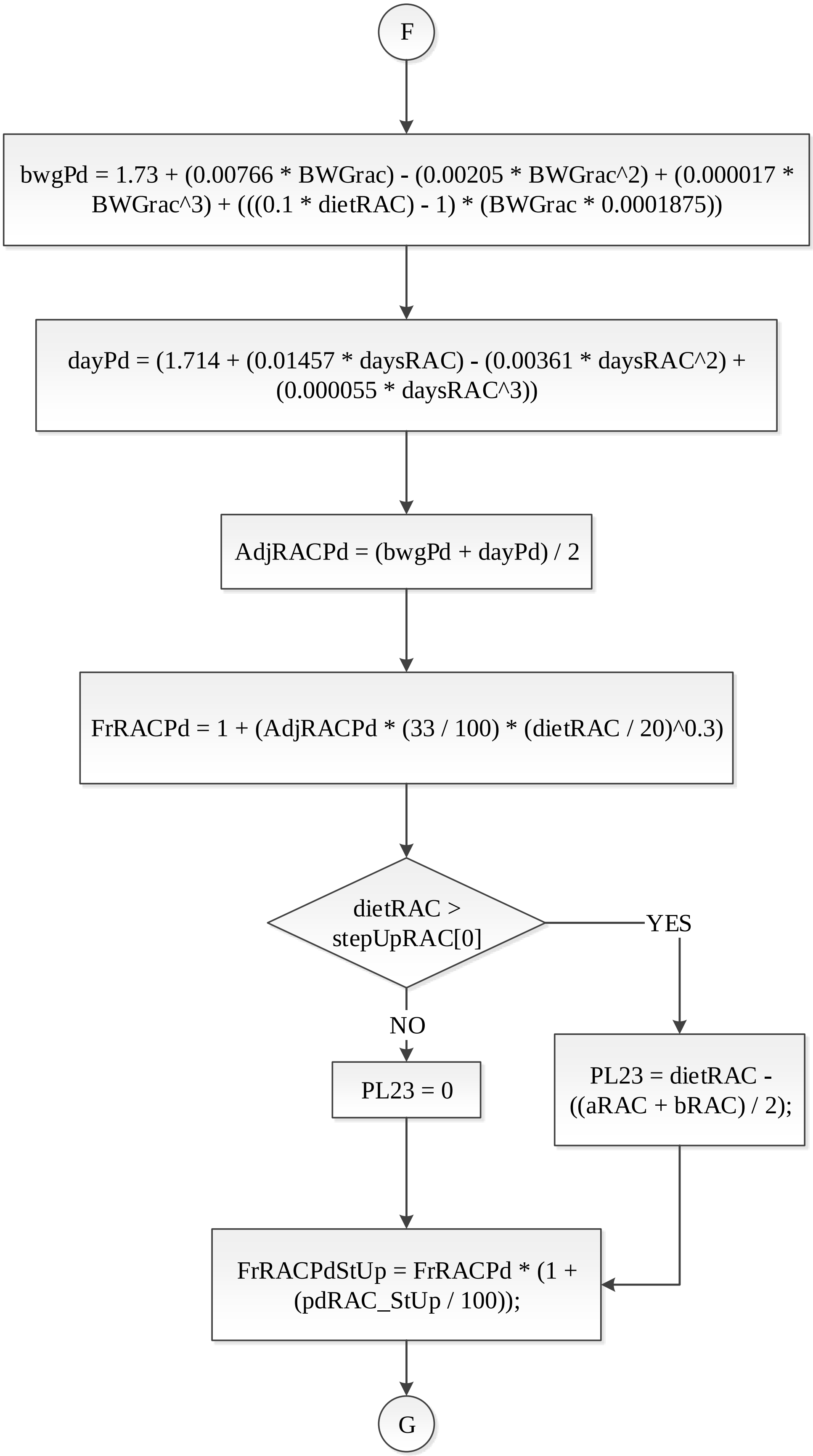

A
If floorSp < minSp
YES
NO
MEI adjusted for floor space
MEI_sp = MEI_T
MEI_sp = MEI_T * (1 – 0.252 * ((floorSp -minSP)/floorSp))
Max DFI
DFI_max = 111 * iniBW^0.803 + 111 * iniBW^0.803 * (LCT_T) * 0.025
MEI_max = DFI_max * dietME
finalDFI = min(DMEI, MEI_T, MEI_sp, MEI_max) / dietME
Metabolizable Energy Intake
MEI = finalDFI * dietME
Standard maintenance ME requirement
SMMER = 197 * iniBW^0.6
B

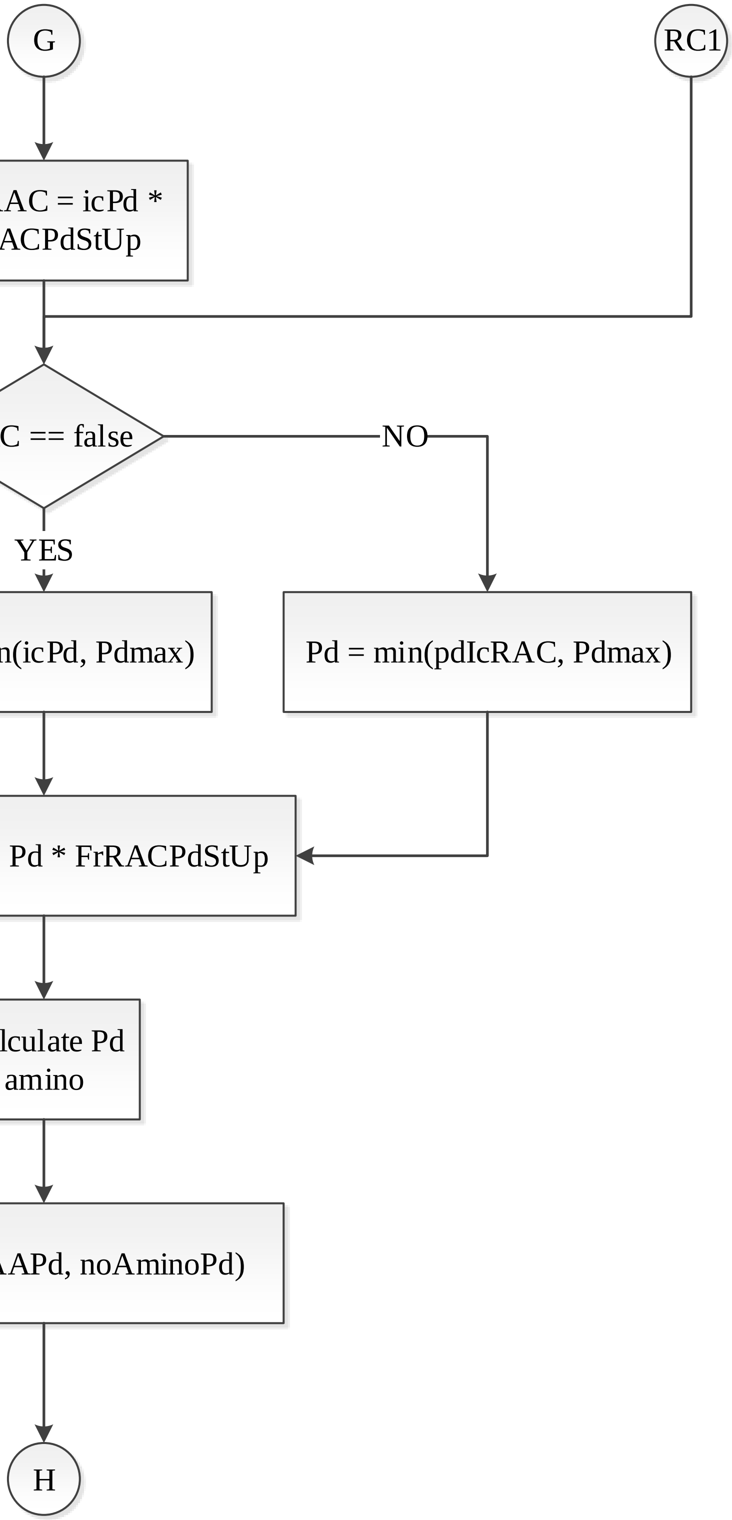

B
T > LCT
YES
NO
SMER adjusted for temp
MMER = SMER * (1 + 0.07425 * (LCT – T))
MMER = SMER
iniBW < BW_dPdmax
YES
NO
Pdmax is hardcoded value eg 150 g/d
Pdmax = Pdmax_d
indexBPmax = 1
YES
NO
Find index for bodyWeight[i] = BWdpdmax
BP_dPdmax = bodyProtein[indexBW]
Set indexBPmax = 0
BPmat = BP_dPdmax * 2.7182
Rcpdmax = (Pdmax_d / (1000 * Bpmat)) * 2.7182
Pdmax = iniBP * 1000 * Rcpdmax * log(BPmat/iniBP)
C

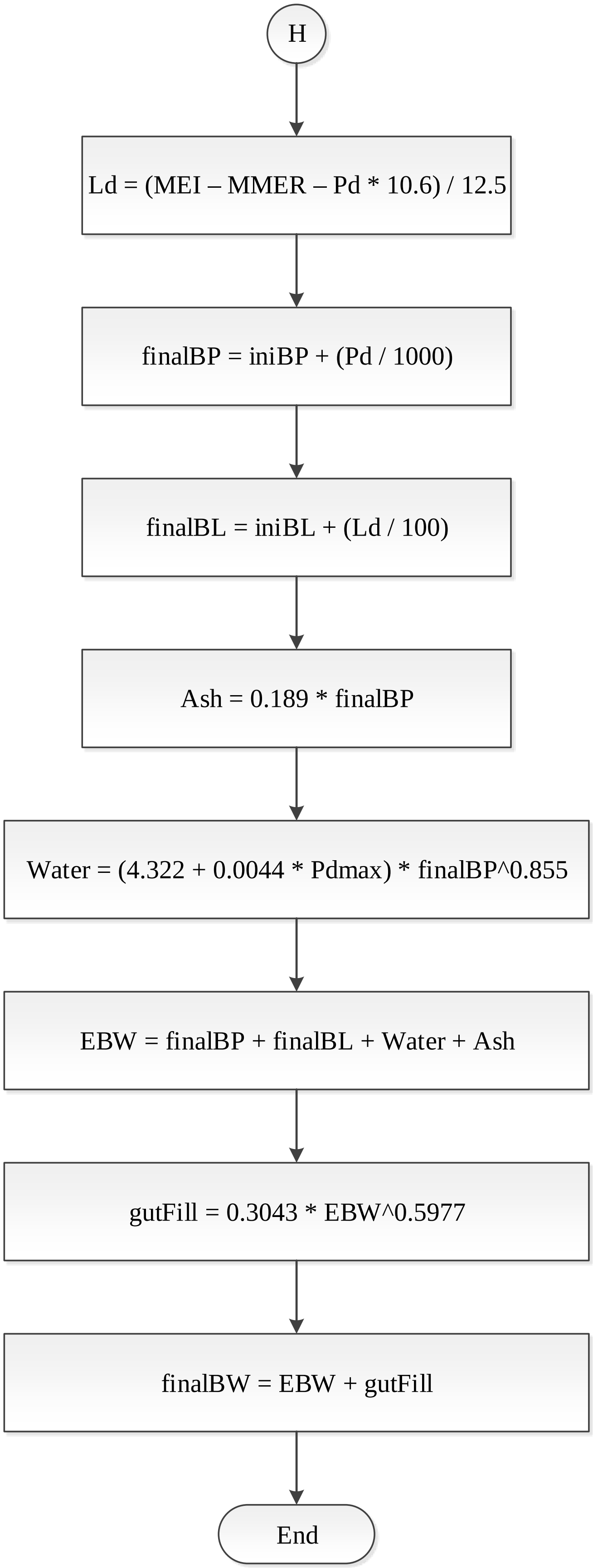

C
Pdest = (30 + (21 + 20 * exp(-0.021 * iniBW)) * (MEI - 1.3 * MMER) * (Pdmax / (125 * 1000)) * (1 + 0.015 * (20 - T))) * adjFact
Protein deposition
Pd = min(Pdest, Pdmax)
YES
icRACuse = true
NO
dayScIn > 10
YES
NO
icPD = Pd
adjDay = 10
adjDay = dayScIn
IcMEI = MEI
dayScIn = 0
YES
NO
adjFact01 = 1
adjFact01 = 1 - ((adjDay / 10) * (1 - 0.79))
D
IM1


D
Pd = adjFact01 * Pd
IcMEI = MEI * (1 + ((adjDay/10) * 0.21))
IcMMER = MMER * (1 - (adjDay/10) * 0.12)
RAC = true
NO
YES
finalMEI = icMEI
BWGrac = iniBW - BWrac
BWGrac < 20
YES
YES
racMEIR = -0.191263 + 0.019013*BWGrac - 0.000443*BWGrac^2 + 0.000003539* BWGrac^3
racMEIR = 0.036
racMEI = 1-(racMEIR*(dietRAC/ 20)^0.7)
finalMEI = racMEI * IcMEI
E


E
IM1
icPd = Pd * (1-(adjDay/10)*0.08)
RAC = true
YES
NO
icRACuse = false
YES
NO
BWGrac = iniBW - BWrac
BWGrac < 20
YES
NO
racMEIR = -0.191263 + 0.019013*BWGrac – 0.000443*BWGrac^2 + 0.000003539*BWGrac^3
racMEIR = 0.036
racMEI = 1 – (racMEIR*(dietRAC/ 20)^0.7)
finalMEI = racMEI * icMEI
No, avoid the loop
F
RC1


F
bwgPd = 1.73 + (0.00766 * BWGrac) - (0.00205 * BWGrac^2) + (0.000017 * BWGrac^3) + (((0.1 * dietRAC) - 1) * (BWGrac * 0.0001875))
dayPd = (1.714 + (0.01457 * daysRAC) - (0.00361 * daysRAC^2) + (0.000055 * daysRAC^3))
AdjRACPd = (bwgPd + dayPd) / 2
FrRACPd = 1 + (AdjRACPd * (33 / 100) * (dietRAC / 20)^0.3)
dietRAC > stepUpRAC[0]
YES
NO
PL23 = 0
PL23 = dietRAC - ((aRAC + bRAC) / 2);
FrRACPdStUp = FrRACPd * (1 + (pdRAC_StUp / 100));
G


G
RC1
pdIcRAC = icPd * FrRACPdStUp
RAC == false
NO
YES
Pd = min(icPd, Pdmax)
Pd = min(pdIcRAC, Pdmax)
noAminoPd = Pd * FrRACPdStUp
Calculate Pd amino
Pd = Min(AAPd, noAminoPd)
H


H
Ld = (MEI – MMER – Pd * 10.6) / 12.5
finalBP = iniBP + (Pd / 1000)
finalBL = iniBL + (Ld / 100)
Ash = 0.189 * finalBP
Water = (4.322 + 0.0044 * Pdmax) * finalBP^0.855
EBW = finalBP + finalBL + Water + Ash
gutFill = 0.3043 * EBW^0.5977
finalBW = EBW + gutFill
End

Where,

DMEI- default metabolizable energy intake, cal/day

MEI- metabolizable energy intake, cal/day

LCT- lower critical temperature, ℃

T- barn temperature, ℃

MEI_T- metabolizable energy intake adjusted for temperature, cal/day

minSp- minimum floor space required for a pig, m^2

floorSp- floor space per pig available in the barn, m^2

MEI_sp- metabolizable energy intake adjusted for floor space, cal/day

DFI_max- maximum daily feed intake, kg/day

MEI_max- maximum metabolizable intake, cal/day

SMMER- standard maintenance metabolizable energy required, cal/day

MMER- maintenance metabolizable energy required, cal/day

iniBW- initial body weight, kg

Pdmax- maximum protein deposition, g/day

BW_dPdmax- body weight after which Pdmax starts to decline, kg

BPmat- body protein at maturity, kg

Rcpdmax- Gompertz rate constant

Pdest- estimated protein deposition, g/day

icPD- protein deposition with effect of immunocastration, g/day

IcMEI- effect of immunocastration on MEI, cal/day

IcMMER- effect of immunocastration on MMER, cal/day

BWGrac- body weight gain on ractopamine, kg racMEIR = effect of ractopamine on required metabolizable energy, cal/day

Ld- lipid deposition, g/day

finalBP- final body protein, kg

finalBL- final body lipid, kg

Ash- ash deposition, kg

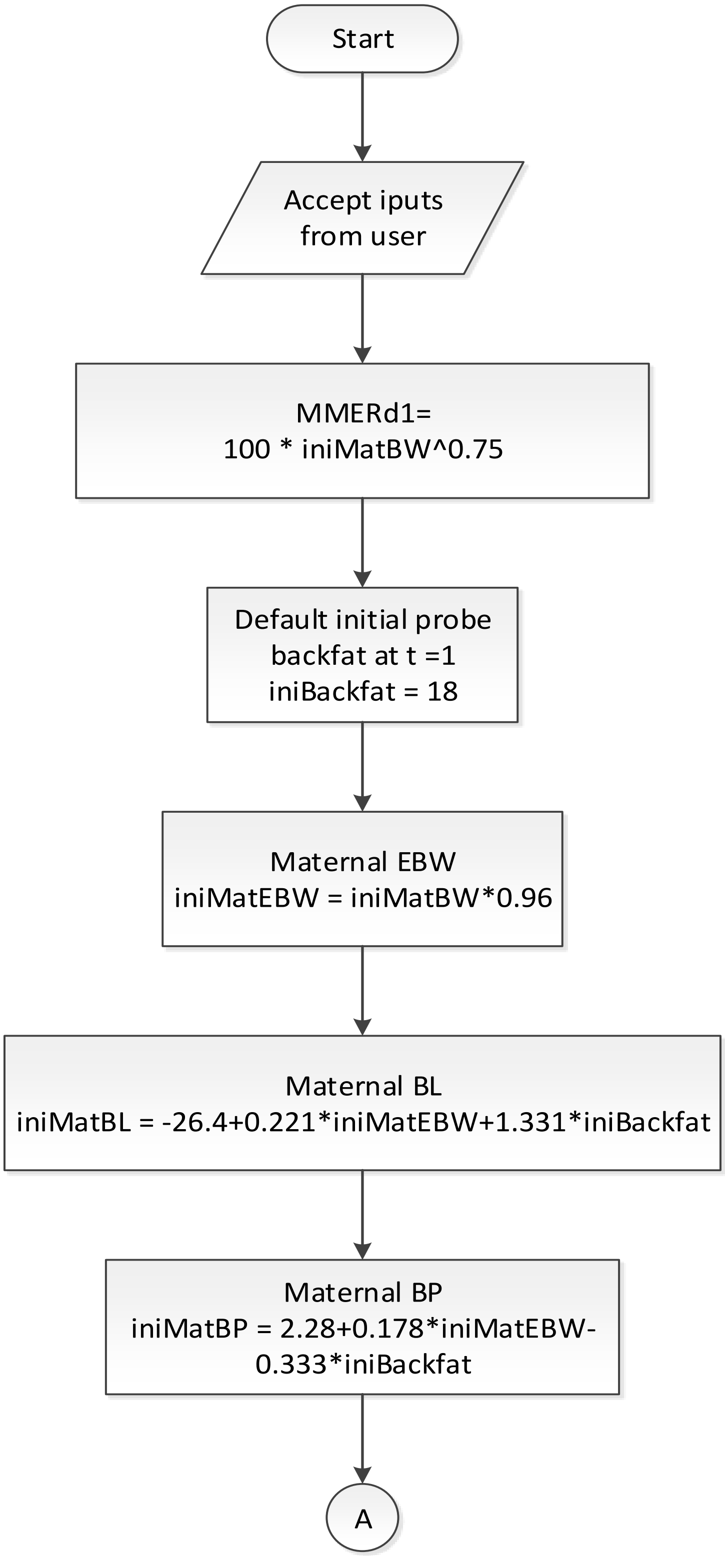
Water- water deposition, kg

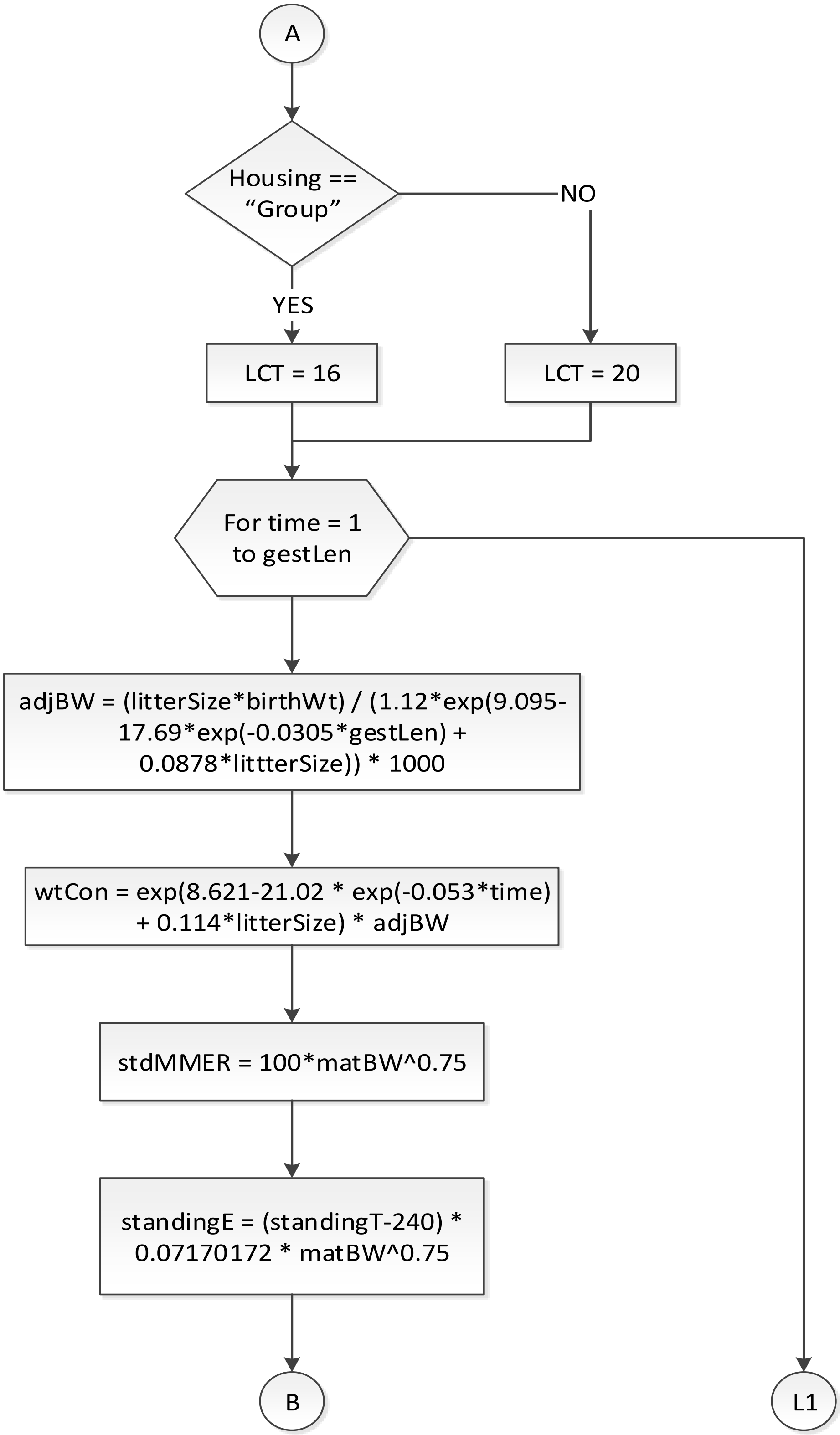
EBW- empty body weight, kg

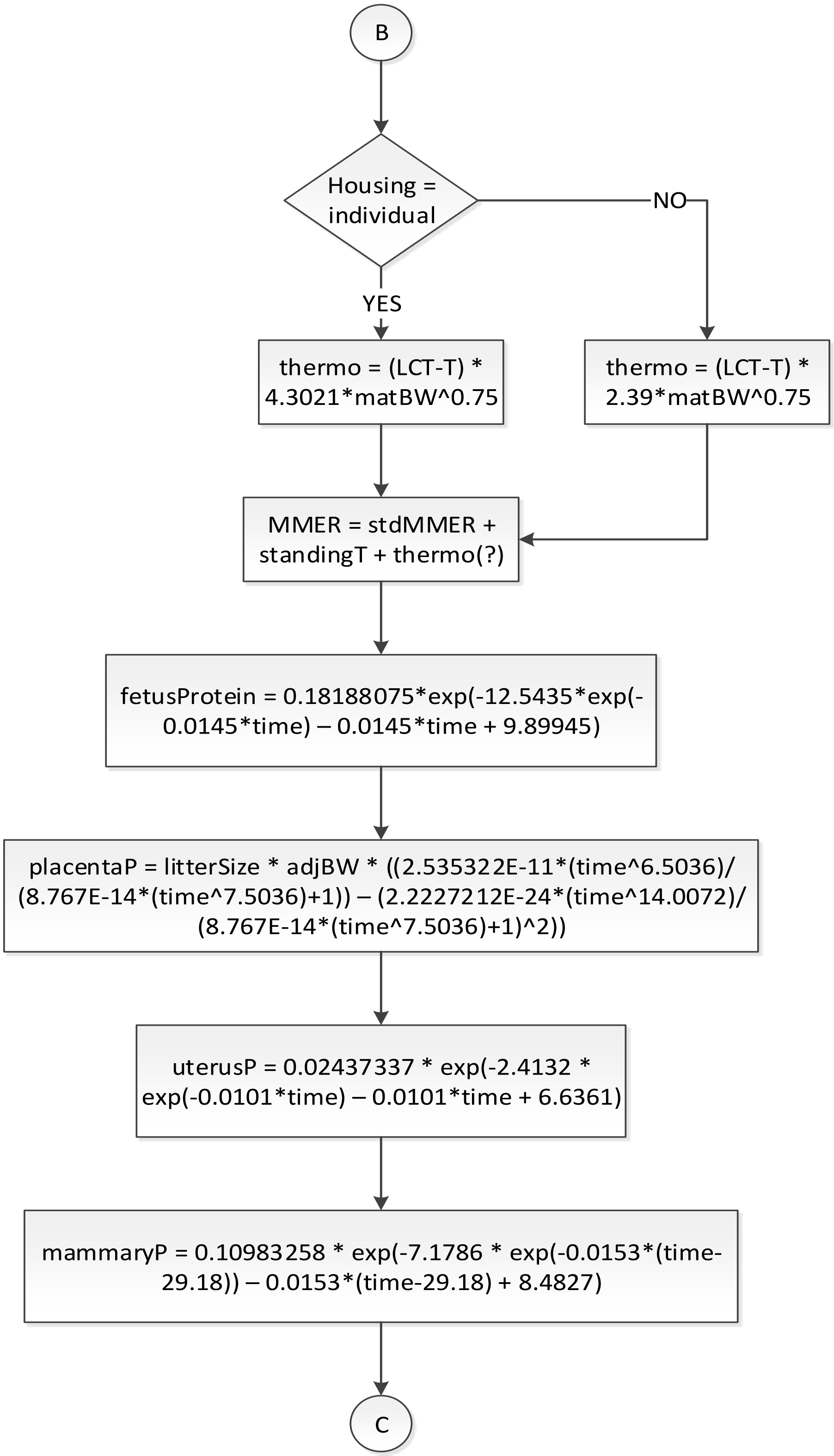
gutFill- gut fill, kg

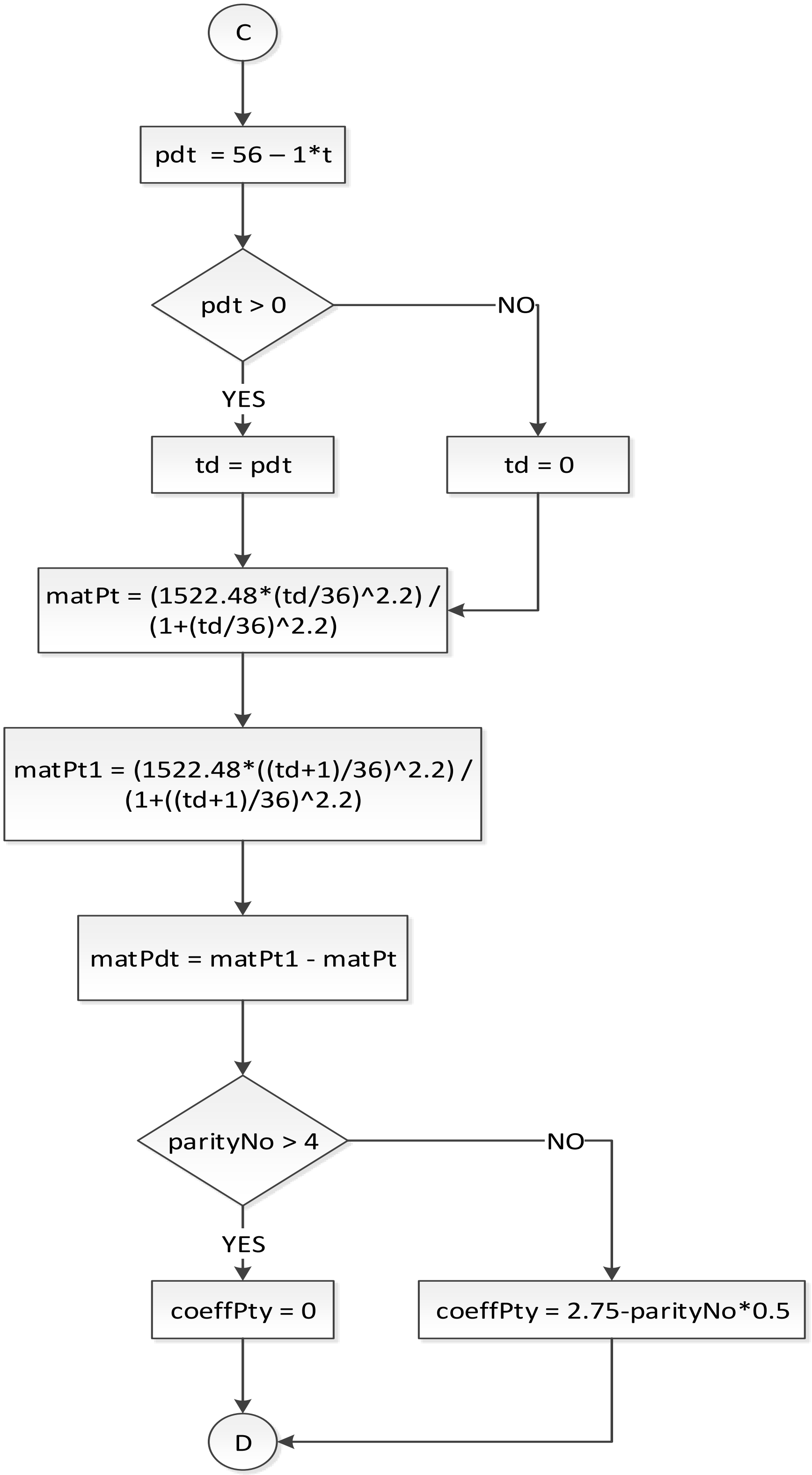
finalBW- final body weight, kg

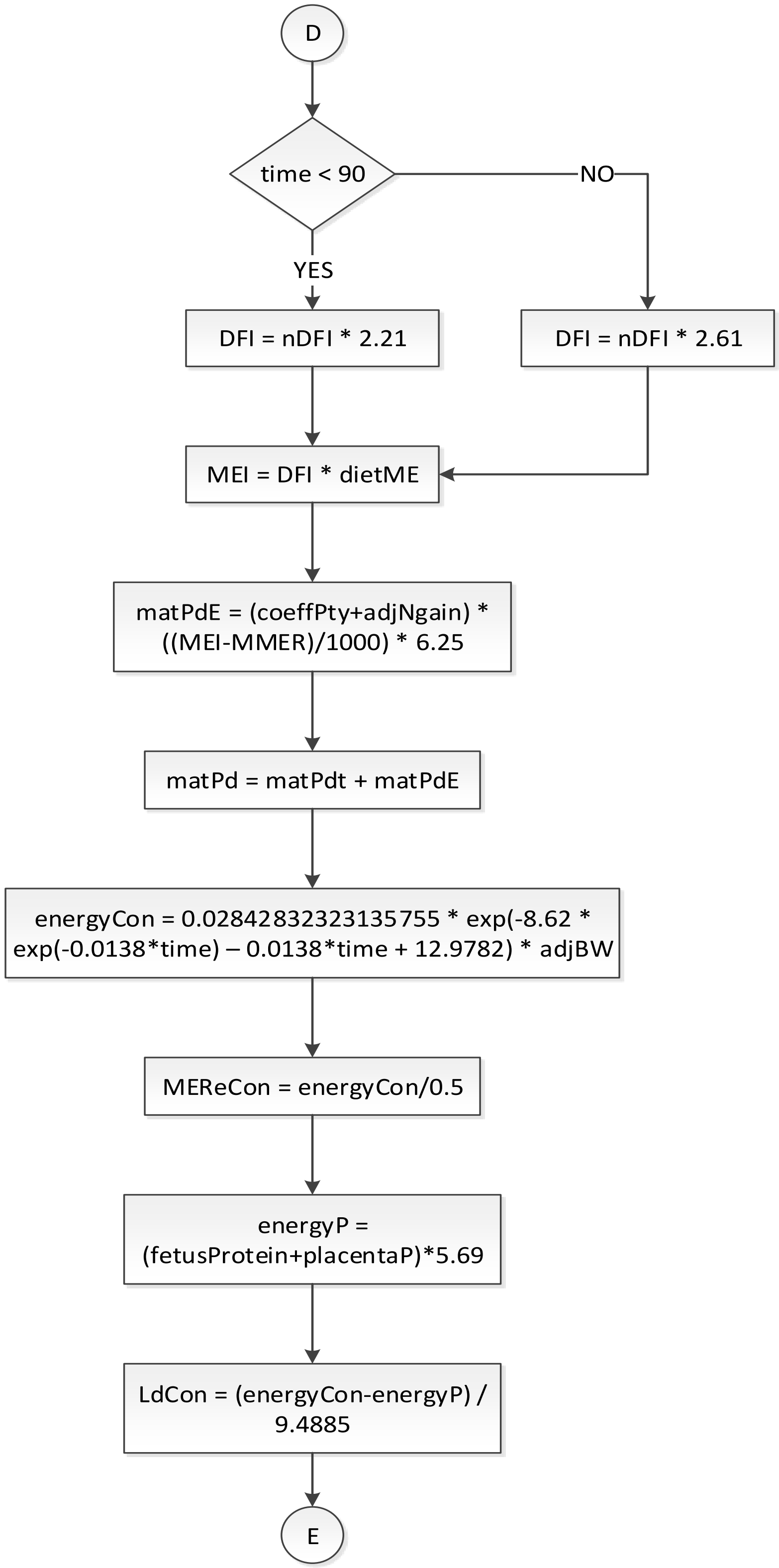
Appendix B: National Research Council model for growth of gestating sows implemented in Pork Production Environmental Footprint (PPEF) model

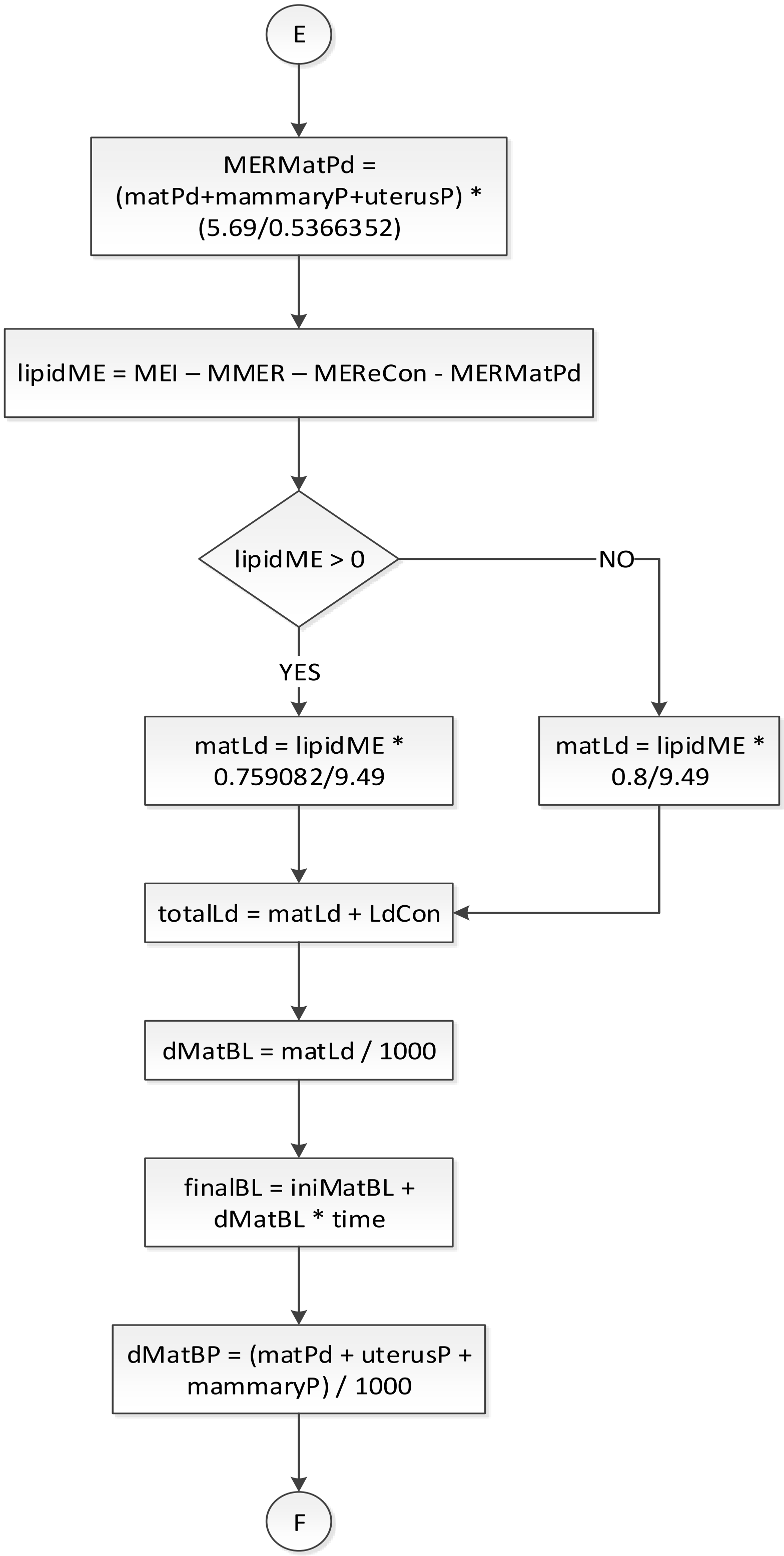


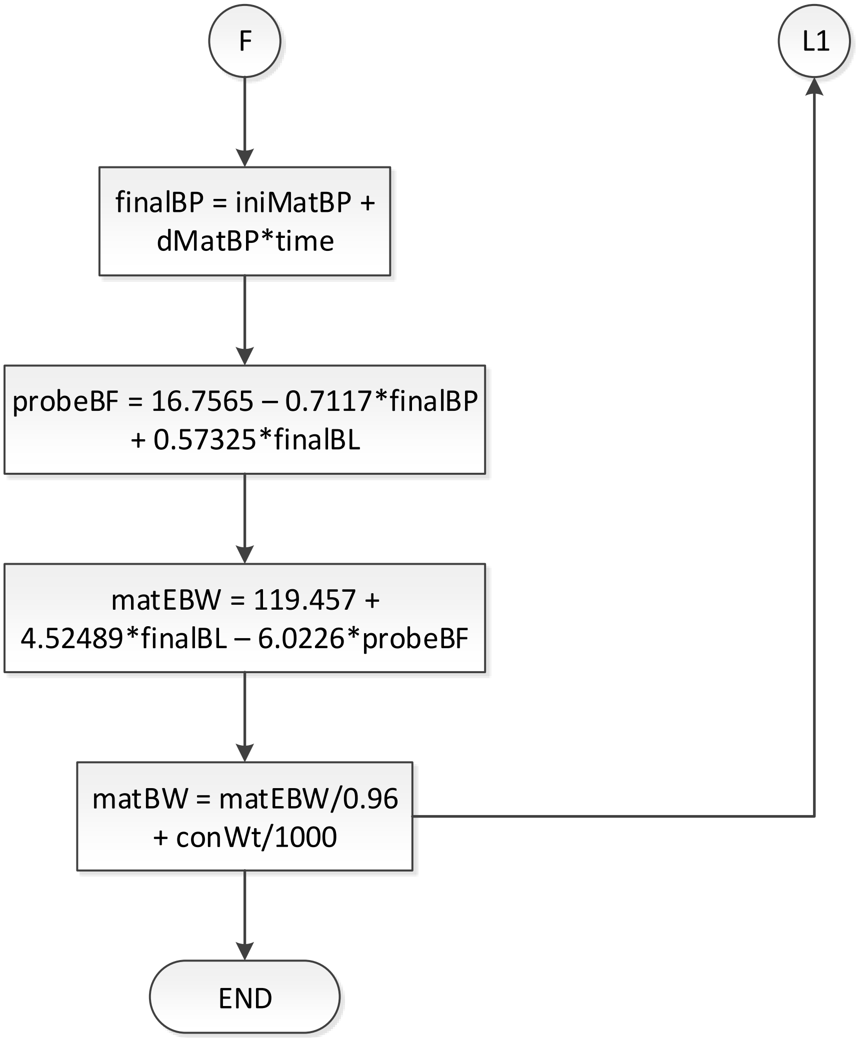

A
Housing ==
"Group"
NO
YES
LCT = 16
LCT = 20
For time = 1
to gestLen
adjBW = (litterSize*birthWt) / (1.12*exp(9.095-17.69*exp(-0.0305*gestLen) + 0.0878*littterSize)) * 1000
wtCon = exp(8.621-21.02 * exp(-0.053*time) + 0.114*litterSize) * adjBW
stdMMER = 100*matBW^0.75
standingE = (standingT-240) * 0.07170172 * matBW^0.75
B
L1


B
Housing = individual
NO
YES
thermo = (LCT-T) * 4.3021*matBW^0.75
thermo = (LCT-T) * 2.39*matBW^0.75
MMER = stdMMER + standingT + thermo(?)
fetusProtein = 0.18188075*exp(-12.5435*exp(-0.0145*time) – 0.0145*time + 9.89945)
placentaP = litterSize * adjBW * ((2.535322E-11*(time^6.5036)/(8.767E-14*(time^7.5036)+1)) – (2.2227212E-24*(time^14.0072)/(8.767E-14*(time^7.5036)+1)^2))
uterusP = 0.02437337 * exp(-2.4132 * exp(-0.0101*time) – 0.0101*time + 6.6361)
mammaryP = 0.10983258 * exp(-7.1786 * exp(-0.0153*(time-29.18)) – 0.0153*(time-29.18) + 8.4827)
C


C
pdt = 56 – 1*t
pdt > 0
NO
YES
td = pdt
td = 0
matPt = (1522.48*(td/36)^2.2) / (1+(td/36)^2.2)
matPt1 = (1522.48*((td+1)/36)^2.2) / (1+((td+1)/36)^2.2)
matPdt = matPt1 - matPt
parityNo > 4
NO
YES
coeffPty = 0
coeffPty = 2.75-parityNo*0.5
D


D
time < 90
NO
YES
DFI = nDFI * 2.21
DFI = nDFI * 2.61
MEI = DFI * dietME
matPdE = (coeffPty+adjNgain) * ((MEI-MMER)/1000) * 6.25
matPd = matPdt + matPdE
energyCon = 0.02842832323135755 * exp(-8.62 * exp(-0.0138*time) – 0.0138*time + 12.9782) * adjBW
MEReCon = energyCon/0.5
energyP = (fetusProtein+placentaP)*5.69
LdCon = (energyCon-energyP) / 9.4885
E


E
MERMatPd =
(matPd+mammaryP+uterusP) *
(5.69/0.5366352)
lipidME = MEI – MMER – MEReCon - MERMatPd
lipidME > 0
NO
YES
matLd = lipidME *
0.759082/9.49
matLd = lipidME *
0.8/9.49
totalLd = matLd + LdCon
dMatBL = matLd / 1000
finalBL = iniMatBL +
dMatBL * time
dMatBP = (matPd + uterusP +
mammaryP) / 1000
F



Where,

MMERd1- maintenance metabolizable energy required on day 1, cal/day

iniBackfat- initial default backfat thickness, mm

iniMatEBW- initial maternal empty body weight, kg

iniMatBL- initial maternal body lipid, kg

iniMatBP- initial maternal body protein, kg

LCT- lower critical temperature, ℃

adjBW- body weight adjustment for litter size and birth weight of piglets, wtCon- weight of conceptus, g

stdMMER- standard maintenance metabolizable energy required, cal/day

standingE- sow’s energy cost of standing, cal/day

thermo- energy spent adjusting for temperature, cal/day

MMER- maintenance metabolizable energy required, cal/day

fetusProtein- protein content of fetus, g

placentaP- protein content of placenta, g

uterusP- protein content of uterus, g

mammaryP- protein content of mammary glands, g

matPt, matPt1, matPdt- time dependent protein deposition, g/day

DFI- daily feed intake, kg/day

MEI- metabolizable energy intake, cal/day

matPdE- energy dependent maternal protein content, g/day

matPd- maternal protein deposition, g/day

energyCon- energy content of conceptus, cal

LdCon- lipid deposition in conceptus, g/day

MERMatPd- metabolizable energy requirement for maternal protein deposition, cal/day

lipidME- ME balance for lipid deposition, cal/day

matLd- maternal lipid deposition, g/day

totalLd- total lipid deposition, g/day

finalBL- final body lipid, kg

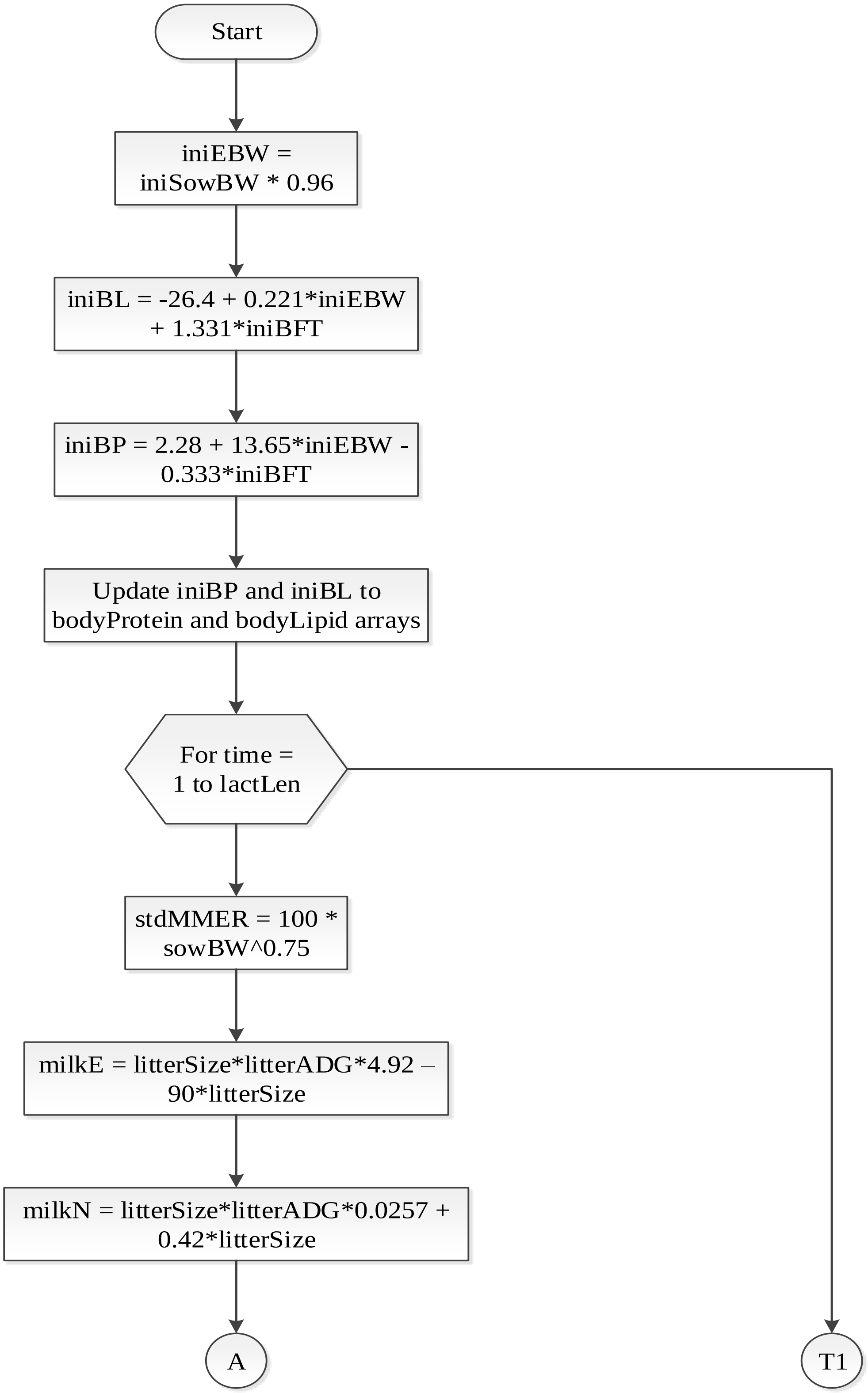
finalBP- final body protein, kg

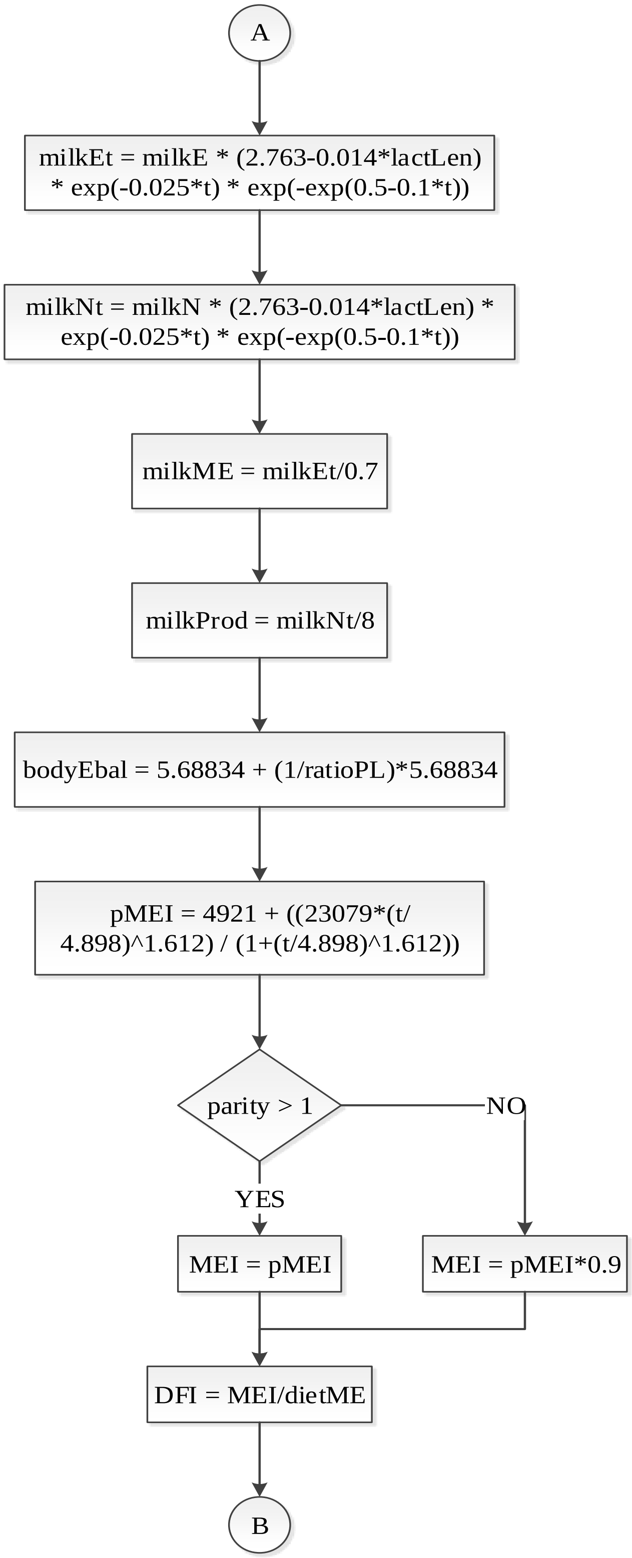
probeBF- probe backfat thickness, mm

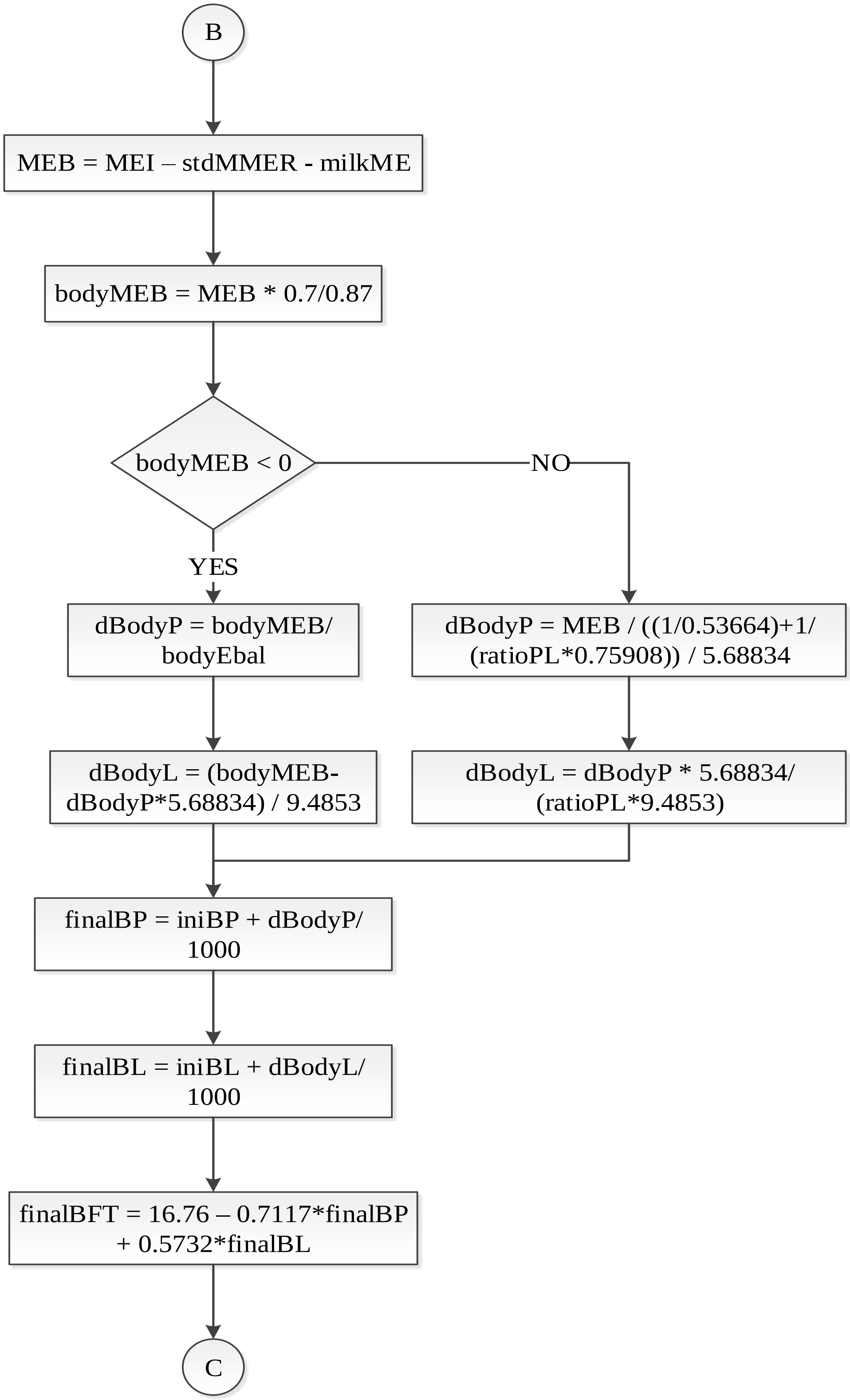
matEBW- maternal empty body weight, kg

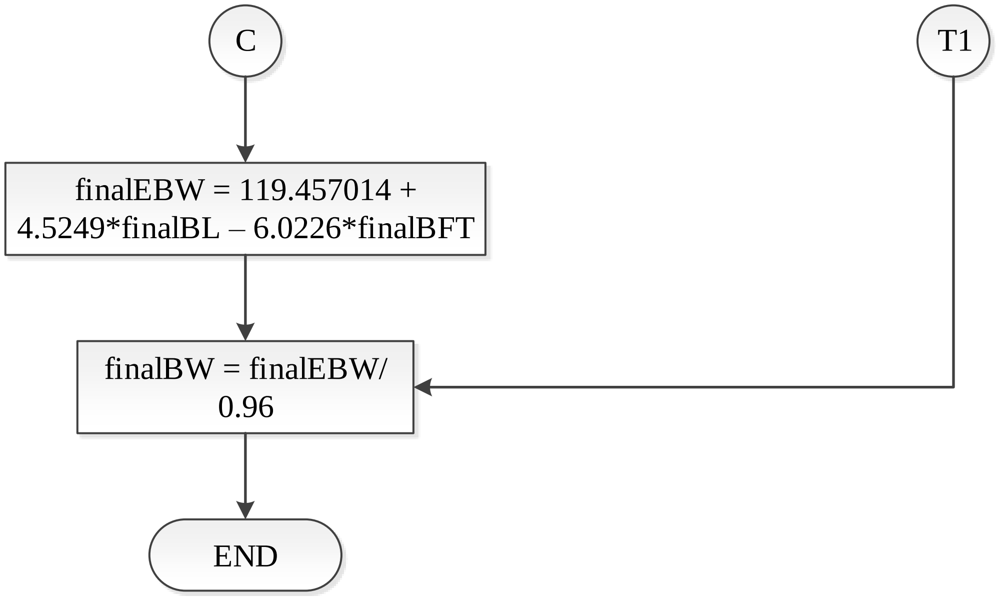
matBW- maternal body weight, kg

Appendix C: National Research Council model for growth of lactating sows implemented in Pork Production Environmental Footprint (PPEF) model




A
milkEt = milkE * (2.763-0.014*lactLen) * exp(-0.025*t) * exp(-exp(0.5-0.1*t))
milkNt = milkN * (2.763-0.014*lactLen) * exp(-0.025*t) * exp(-exp(0.5-0.1*t))
milkME = milkEt/0.7
milkProd = milkNt/8
bodyEbal = 5.68834 + (1/ratioPL)*5.68834
pMEI = 4921 + ((23079*(t/4.898)^1.612) / (1+(t/4.898)^1.612))
parity > 1
NO
YES
MEI = pMEI
MEI = pMEI*0.9
DFI = MEI/dietME
B


B
MEB = MEI – stdMMER - milkME
bodyMEB = MEB * 0.7/0.87
bodyMEB < 0
NO
YES
dBodyP = bodyMEB/ bodyEbal
dBodyP = MEB / ((1/0.53664)+1/ (ratioPL*0.75908)) / 5.68834
dBodyL = (bodyMEB- dBodyP*5.68834) / 9.4853
dBodyL = dBodyP * 5.68834/ (ratioPL*9.4853)
finalBP = iniBP + dBodyP/ 1000
finalBL = iniBL + dBodyL/ 1000
finalBFT = 16.76 – 0.7117*finalBP + 0.5732*finalBL
C



Where,

iniEBW- initial empty body weight, kg

iniBL- initial body lipid, kg

iniBP- initial body protein, kg

stdMMER- standard maintenance metabolizable energy required, cal/day

milkE- mean milk gross energy output, cal/day

milkN- milk N output, g/day

milkME- metabolizable energy required for milk production, cal/day

milkProd- milk production, kg/day

pMEI- predicted metabolizable energy intake, cal/day

MEI- metabolizable energy intake, cal/day

DFI- daily feed intake, kg/day

MEB- metabolizable energy balance, cal/day

dBodyP- change in body protein, g/day

dBodyL- change in body lipid, g/day

finalBP- final body protein, kg

finalBL- final body lipid, kg

finalBFT- final probe backfat thickness, mm

finalEBW- final empty body weight, kg

finalBW- final body weight, kg